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### Verification of energy consumption modelling in a vehicle under operating conditions of a transport company

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Summary. This paper presents the results of operating a car in the variable national and international infrastructure. The research aimed to evaluate the implementation of the AETR Act and the impact of infrastructure and vehicle loading capacity on fuel consumption (both the conventional and dissipated energy). In the calculations mathematical formalism of the adopted structural model was applied.

Key words: transport logistics, communication infrastructure, structural modeling, operational factors, fuel consumption, digital recording.

### INTRODUCTION

The increasing globalization of the world economy requires a search by car transport companies of more efficient methods of their business. They allow for gaining competitive advantage in the international division of freight and distribution services [9,14,15].

As more countries achieve the advanced economic development, or even reach an emergency crisis [16], more and more commonly cars are equipped with different electronic telemetry devices to record their location, operational course or the current exchange of logistic information [4.10]. The range of such technical equipment includes, among others, the GTS systems, automatic vehicle control systems, speed limiters, electronic record of operating parameters (tachographs). In the future they are intended to become elements of the "black box" in a vehicle [4,6].

The ultimate goal of any business is profit [12]. The efforts aim, therefore, at the achievement of successful economic balance, after incurring undoubtedly large costs, and in some cases also addition of legally compulsory additional equipment [14.17].

Key features and benefits of transport logistics as a scientific field have been recognized in developed countries and successfully implemented. This purpose is served by research into vehicle kinetic energy, its efficient use and losses within different infrastructure, or influence of the flow of traffic on transport engineering [1, 2, 3, 18, 19, 20].

The purpose of this study is to analyze the course of operation of a vehicle in the selected shipping company providing domestic and international transport services. Specifically, in terms of the observation of AETR Act, vehicle kinetic energy expenditure, the losses depending on the speed, infrastructure and capacity. The analysis was based on the record of a digital tachograph type Stoneridge Electronics, in conjunction with the authors' previous studies on the structural modeling of kinetic energy losses in vehicles [4,5].

### THE RESEARCH METHODOLOGY

The adopted research methodology involved the truck MAN TGL 12.180, dated from 2007, as the object of studies.

The technical data of the vehicle:

- Weight: 5890 kg,
- Maximum permissible mass: 11990 kg,
- The largest allowable axle load: 82.32 kN,
- Engine capacity: 4580 cm
- Engine power: 1322 kW (180 hp),
- 6-speed manual gearbox.

The analysis was performed of the record from *Stoneridge Electronics* digital tachograph, model SE 5000.

The technical data of the measuring device:

- Operating temperature from -25 °C to 70 °C,
- Certification and approval for use in accordance with the EU - ITSEC 'level E3 - high ", No of approval: e5 - 0.02;

 Electromagnetic compatibility according to the EU Commission Directive 95/54/EC.

Prior to research the tachograf had been secured by authorized personnel, and during the implementation of studies, there was no manipulation or modification of the equipment or the speed sensor [13].

### **RESULTS AND ANALYSIS**

The results of the reading of *Stoneridge Electronics* tachograph's record of a vehicle in domestic freight are presented in Table (1), whereas in the international one - in Table (2).

Route I. Biłgoraj - Belzec - Cieszyn,

Route II. Mielec - Belzec - Bilgoraj,

Route III. Bilgoraj - Przeworsk - Bilgoraj,

Route IV. Kolbuszowa - Przeworsk - Belzec - Bilgoraj - Przeworsk - Machowa,

Route V. Machowa - Tarnow - Mielec - Tarnobrzeg

Route A - Cieszyn - Cadca (SK) - Mielec,

Route B - Bilgoraj - Mielec - Tarnow - Martin (SK) Route C - Martin (SK) - Cadca (SK) - Cieszyn.

The analyses of the digital tachograph printouts in domestic freight (Table 1) and international freight (Table 2) showed that the drivers had complied with the applicable regulations concerning the working time (according to AETR). Only in two cases the digital recording suggested the exceeding of the total time of the driver's work, however, according to Art. 15, Act of April 16, 2004 on the working time of drivers, the cases must be considered acceptable (Journal of Laws No. 92, item. 879).

The obtained digital recording operating data (Table 1 and Table. 2) showed that, e.g.:

- with a similar driving time on the national road (0,5.0.5) and (10.05) and international one (04.05), there occurred differences in the length of route,
- on international routes of similar length (05.05 and 11.05) there were significant differences in the length of driving time,
- on similar routes (5-6.05), at the existing driving conditions, a highly loaded vehicle (Table 3) could cover the distance faster then a vehicle without load.

The mathematical formalism of probability distribution of driving speed oscillogram amplitudes in the existing communication infrastructure is presented in the form of an empirical relationship (formula 1÷3):

$$y_1 = -0.0393x^5 + 1.0342x^4 - 9.7313x^3 + 40.35x^2 - 71.889x + 42.842$$
$$R^2 = 0.7768$$

$$y_2 = -0.0358x^5 + 0.9635x^4 - 9.333x^3 + 39.863x^2 -$$
  
71,719x+43,617  
$$R^2 = 0.8741$$
(1÷3)

No	Description of daily	Travel date (Ro	ute No I - V)			
INU	activities	04.05.11/I	06.05.11/II	09.05.11/III	12.05.11/IV	13.05.11/V
1.	Driving the vehicle	8 h 33 min.	4 h 07 min.	5 h 36 min.	8 h 02 min.	3 h 0 min.
2.	Other work	27 min.	1 h 22 min.	1 h 15 min.	1 h 25 min.	59 min.
3.	Rest	15 h	9 h 50 min.	17 h 09 min.	14 h 33 min.	8 h 08 min.
4.	Distance covered	513 km	220 km	286 km	405 km	129 km
5.	Average speed	60 km/h	53 km/h	51 km/h	50 km/h	43 km/h
6.	Total run time	9 h	5 h 25 min.	6 h 51 min.	9 h 27 min.	3 h 59 min.

Table 1. The results of the reading of Stoneridge Electronics tachograph's record of a vehicle in domestic freight

<b>Fable 2.</b> The results of the	e reading of S	Stoneridge Electronics	tachograph's record	ofav	vehicle in	international	freight
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No	Description of daily	Travel date (Route No VI - V	/II)	
INO	activities	05.05.11/A	10.05.11/B	11.05.11/C
1.	Driving the vehicle	8 h 20 min.	8 h 47 min.	7 h 55min.
2.	Other work	1 h 56 min.	1 h 17 min.	2 h 55 min.
3.	Rest	13 h 44 min.	13 h 54 min.	13 h 10 min.
4.	Distance covered	428 km	453 km	432 km
5.	Average speed	51 km/h	52 km/h	55 km/h
6.	Total run time	10 h 14 min.	10 h 04 min.	6 h 51 min.
7.	Time of the driver's availability	-	2 min.	-

Гat	le	3.	The results	of measuring	fuel	consumption for	or variable	loading	capacity,	considering	average	speed
						real real real real real real real real			· · · · · · · · · · · · · · · · · · ·			- <b>F</b>

No	Type of route by date of travel	Fuel consumption in l/100 km	Loading capacity of the vehicle 100% load in% of route	Loading capacity of the vehicle 50 % load in% of route	Without load 50 % load in% of route	Average speed of travel km/h
1.	5-6.05.2011	20,34 17,34	86,0 14,4	- 24,9	14,0 60,7	59,5 52,9
2.	9-13.05.2011	16,79 18,37 17,20	24,0 55,4 29,8	76,0 - 53,6	- 44,6 16,6	50,5 52,4 49,2

Tabla	4	The maguilta	of magazing onto	of fuel	acmantia		waniahla tu	an an ant i	n fue at must sugar	at arrana aa	amaad
rable 4	۰.	The results	of measurements	of fuel	consumptio	пш	variable tr	ansport i	mirastructure	at average	speed

	Tupe of route	Fuel	Type of communic	ation infrastructure	in the whole route,	/0
No	by date of travel	consumption l/100 km	Freeways	European ways	Local ways	Average speed km/h
1.	5-6.05.2011	20,34 17.37	- 13,8	70,6 50,9	29,4 35,3	59,5 52,9
2.	9-13.05.2011	16,79 18,37 17,20	- 7,4 -	7,5 39,4 33,1	92,5 53,2 66,9	50,5 52,4 49,2

 $y_3 = 0,0086x^5 - 0,2391x^4 + 2,2732x^3 - 8,504x^2 + 12,311x - 1,0867$ 

 $R^2 = 0,7395,$ 

where:

*y1 (international road), y2 (expressway), y3 (national road)* – level of amplitude probability distribution [%]);

x -speed interval [km / h].

This is the result of frequent modernization and repair of roads, lower standards of part of the route and, consequently, their lower speed limits as well as variable number of users [7].

Mathematical formalism of the adopted fuel consumption model taking into account the conditions of traffic infrastructure flow and utilization of the vehicle capacity is presented by the following relationship:

$$Gpg 1-3 = Aa + Bb + Cc + xex + Yan + Zwo, \qquad (4)$$

where:

 $Gp_{g_{l,3}}$  - global (operational) fuel consumption [l/100 km],

A, B, C - the percentage of capacity on a route,

a, b, c - coefficients of the fuel consumption relative to loading capacity (0.29, 0.14, 0.07),

X, Y, Z-percent share of the infrastructure along the route,

*ex,an,wo* – traffic flow rates of high speed road, international (highway) road, provincial (voivodship) road (35.0, 13.4, 43.7).

It follows that:

$$Gp_g Gp_s = - (Aa + Bb + Cc + xex + Yan + Zwo$$
 (5)

where:

 $Gp_s$  - loss of fuel related to operational load capacity of a vehicle  $(Gp_p)$  and traffic flow  $(Gp_p)$ ,

 $Gp_{\sigma}$  - global fuel consumption en route.

A more detailed analysis of fuel consumption, based on the calculated coefficients of the used load capacity of vehicles (WWT), in different communication infrastructure (at approximate average speeds) shows the corresponding fuel consumption - GP (expression 6÷8):

$$\begin{split} Gp_{g1} &= 24.0a + 76.0b, \\ Gp_{g2} &= 55.4a + 44.6c, \\ Gp_{g3} &= 29.8a + 53.6b + 16.6c, \, (6\div8) \end{split}$$

where:  $Gp_{g1} \div Gp_{g2} = 16,79 \div 18,37;$  a = 0,29, b = 0,14,c = 0,07.

On the 05-06.05.2011 (Table 3) with 100% load at 86% of vehicle route and at 14% without load, the fuel consumption was 4.54 l, with the total consumption of 20-34 l / 100 km.

On the 09-13.05.2011 (Table 3) the loading capacity utilization causes such results as:

when driving a vehicle loaded 50% over 24% of the route and 50% over 76% of routes per share of 92.5% of the provincial (voivodship) road, the fuel consumption associated with the vehicle loading is 6.94 l;

- For example, by driving the entire route with 100% utilization of load capacity, the vehicle would burn 26.1 l, with 50% capacity used 6,30 l (at 7.4% of the high speed way and 39.4% international road as well as 53.2% of the provincial (voivodship) road);
- When driving on the route with 100% capacity used in its middle (55.4%) and in the second part (44.6%) without load, the fuel consumption for this transport amounted to 6.6 l;
- When driving on the road with the participation of 29.8% - 100% load, 53.6% with 50% load and 16.6% without load, at 33.1% share of international road and 66% provincial road, the fuel consumption associated with the transport of cargo amounted to 5.86 l.

Dependencies (1÷2) represent the amplitude probability distributions taken as typical for the occurring in the studies traffic flow infrastructure [6]. On their basis, and on the basis of the distributed energy rates applicable for the infrastructure (WRE), an attempt was made to estimate the total value for the acceleration and deceleration phase of the vehicle speed. And so, in the case international (highway) road, WRE is 13.4%, in case of high speed way 35.0%, and for the provincial (voivodship) - 43.7% (expression 1÷3).

The analysis of the estimated loss of kinetic energy associated with the traffic flow of vehicles shows that:

a) on the 04 - 06/05/2011 (Table 4) - over 70.6% of the international road, the kinetic energy dissipation associated with the acceleration and deceleration phase of a vehicle speed was 1.92 l, and for driving on the provincial road (29.4% of the route) - 2.61 l (at the consumption of 20.34 l/100 km) which amounted to the total of 4.53 l;

b) on the 09-13.05.2011 (Table 4) – over 92.5% of the provincial road, the loss of dissipated fuel was 6.94 liters, at 16.79 1/100 km overall fuel consumption, in the case of participation of three types of communication infrastructure, with over 50% share of provincial road, the total loss amounted to 6.61 l at 18.37 1/100 km consumption, in the case of 31.1% share of international (highway) road and 66.9% of provincial road the total kinetic energy loss amounted to 5.78 l, at the consumption of 17.1 1/100 km.

The figures (estimates) based on field tests of the vehicle and the above-presented expressions point out at the possibility of a wider scientific analysis of energy consumption in transport infrastructure [18,19]. This is important in optimizing fleet management and operation of a transport company at international and national levels. Further studies support the theory that probability analyses, performance indicators from computer simulation models developing subsequent traffic flows, the related fuel consumption and statistical significance tests of the processes involved, will guarantee reliable results despite the random nature of the operational processes occurring here [8.11].

### CONCLUSIONS

From the research carried out and attempt at a detailed analysis of the occurring operational dependencies in the national and international transport logistics the following conclusions of general character can be drawn:

- a digital record of a vehicle operation is a documented, important source of information not only for administrative control and law enforcement authorities, but due to its additional features and software is becoming an indispensable tool for scientific analysis serving to optimize the vehicle's work;
- progressive "digitalization" of a vehicle is particularly important in modeling operational processes, especially in research on intensity of energy consumption, resulting from a deepening energy crisis of conventional fuels;
- even with the wide participation of the existing global telemetry systems it is possible to obtain the necessary information with other methods (e.g. analysis of statistical significance of the processes) to optimize the management of fleet transport company. They have to be developed in order to increase its competitiveness in the proper selection of routes, loading capacity and reduction in fuel consumption. A special role here is played by a logistics specialist and a legislative adviser in enterprise management, familiar with the principles of their abstract (model) and systematic utilization [12].

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### WERYFIKACJA MODELOWANIA ENERGOCHŁONNOŚCI POJAZDU W WARUNKACH EKSPLOATACYJNYCH PRZEDSIĘBIORSTWA TRANSPORTOWEGO

Streszczenie. W pracy przedstawiono wyniki badań eksploatacyjnych samochodu w zmiennej infrastrukturze krajowej i międzynarodowej. Przedmiotem badań była ocena realizacji ustawy AETR oraz wpływu infrastruktury i wykorzystania ładowności pojazdu na zużycie paliwa (konwencjonalne i energii rozproszonej). W obliczeniach wykorzystano formalizm matematyczny przyjętego modelu strukturalnego.

Słowa kluczowe: logistyka transportowa, infrastruktura komunikacyjna, modelowanie strukturalne, czynniki eksploatacyjne, zużycie paliwa, zapis cyfrowy.

# The hierarchy of impact of technical and economic factors on farmers' dissatisfaction with orchard sprayers

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Summary. There has been a hierarchy of technical and economic factors affecting the satisfaction of the farmers who own orchard sprayers available on the market in Poland. The most important factors, which cause dissatisfaction with the market offer of orchard sprayers, are: too high a price to purchase the sprayer, followed by high prices of spare parts and high costs of services provided by the service personnel.

Key words: orchard sprayer, assessment, hierarchy.

### INTRODUCTION

An important role in agricultural production costs is played by the costs of mechanization. In the fruit farms their participation depends on the participation of the orchards in the structure of agricultural farms, which ranges from 23 to 68% [4]. A correct choice of orchard sprayer is an important factor in the costs of chemical protection in the orchards. Available literature presents traditional methods for optimizing the selection of farm machinery including orchard sprayers [1] as well as shows the proposal of new algorithms [5, 2, 8]. The analysis of the current status, in which there are many models of orchard sprayers that differ not only on price but also design solutions and the value of technical and operating parameters, obliges these methods to take into account a number of new criteria. These criteria include the technical and economic factors that affect the efficiency of orchard sprayers and thus the satisfaction of fruit growers with their possession. The authors are well acquainted with opinions of the owners of owned fruit farms expressing dissatisfaction with the sprayers. Thus there comes the need for research to identify and prioritize in order of importance the factors that cause of dissatisfaction of the owners with owned orchard sprayers. Knowledge of the hierarchy will add to knowledge of the selection criteria for an orchard sprayer. This knowledge will also

be useful to producers of fruit sprayers to fit of the market offer to the needs of the farmers.

The aim of this study was to prioritize the most important technical and economic factors that cause dissatisfaction of farmers with sprayers available in the market.

### **RESEARCH METHODS**

In terms of the significance of technical and economic factors that cause dissatisfaction of farmers with sprayers available in the market of fruit the prioritization was made using expert and mathematical method known in literature under the name of the expert evaluation method [6] as well as the Delphi method [9]. In the initial stage of research based on the experiences from own studies [7,3,10] and interviews with the owners of 28 fruit farms technical and economic factors that have impact on the discontent of growers offered on the market orchard sprayers were distinguished. The identified factors are summarized in Table 1. The identified factors were included in the questionnaire prepared for the test, which was delivered to the experts.

Considering the large number of factors in order to facilitate an expert assessment procedures objective tree was used, which is based on a combination of factors in groups and evaluating separate groups of factors and a separate assessment of factors in group [7,3]. So six groups of factors of the so called second level were distinguished. In each group, 3 to 6 factors were distinguished that were affecting the group, and indirectly the main objective, i.e. dissatisfaction of farmers with sprayers available in the market.

According to the principle of the target tree it is assumed that the impact of six groups of factors (level II targets) on the main goal is 100%. It was similarly assumed, that the impact of factors in this group in total

Factor label	Factor name
C1	Inadequate technical and operational parameters
C 11	Insufficient capacity of the pump in relation to demand
C 12	Insufficient fan output
C 13	Inadequate storage capacity
C 14	Turning radius too large
C 15	Adverse fan gear ratio
C2	Dimensions of the sprayer and design solutions inadequate to applied technologies and working conditions
C 21	No section compensation
C 22	Too little protection of components susceptible to damage
C 23	Limited access to a liquid tank
C 24	Too high width and wheelbase
C 25	Irregular snap output
C 26	Inadequate lighting or its thereof
C3	Unsatisfactory reliability and efficiency of service and access to spare parts
C 31	sprayer failure rate too high
C 32	Unsatisfactory access to spare parts and / or inadequate supply of spare parts
C 33	Unsatisfactory work of service staff (eg, too long waiting for the arrival of service staff)
C4	Manufacturer's range of accessories too limited
C 41	No braking system manufacturer in the offer
C 42	No manufacturer's offer for choice of sizes and types of tires
C 43	No manufacturer offers for choice fan equipment
C 44	No possibility to choose the type sprayer control components
C 45	Lack of facilities to facilitate the preparation of the solution, and rinse containers in manufacturer's offer
C5	The adverse factors affecting the ergonomics and the comfort of operation
C 51	Ease to rinse tank after the treatment
C 52	Limited access to the main control valve
C 53	Too high level of noise generated by fan
C 54	Insufficient access to the tank
C 55	Unable to reverse without PTO switching off
C 56	Limited access to parts subject to adjustment, maintenance or replacement (eg filters, sprayers)
C6	Unsatisfactory economic aspects
C 61	Too high price to purchase the sprayer
C 62	Too high costs of services provided by service departments
C 63	Too high prices of spare parts

Table 1. Summary of technical and economic factors of II and III order affecting the dissatisfaction of fruit growers with the orchard sprayers

is also 100%. Second order factors influence the main objective and the impact of factors centered around the second order factor on that factor is called the local priority. So the effect of third level factors on the level of the main objective is called the system priority [7,3]. The importance of different groups of factors and factors in the group was evaluated by an expert through a break of 100%, respectively, in the order of importance among the various groups of factors, and 100% for individual factors in the group. In this way, the expert considering separately the validity of the groups of factors and, separately, the validity of the factors in this group had an easier task because at the time he focused on a small number of factors. In addition, an expert was given the opportunity to add and evaluate other factors that were not included in the questionnaire research, which were considered important by him. On the basis of expert assessments values for local priorities were produced. The values of system priorities were obtained by multiplying the local priority value of IIIrd order factor by the local priority value of IInd order factor. System priority values were expressed in percentages and their sum was 100%.

Group of experts were the owners of fruit farms, who were elected on the basis of self-assessment and assessment by the people conducting research. Assessment of the expert fitness to take part in the research included such criteria as practical experience in the orchard production, field experience in the use of orchard sprayers as well as theoretical and practical knowledge of modern solutions in the orchard sprayers. It was also required that an expert's work experience at the farm was not less than 5 years.

The experts represented the farms in the counties of Grójec, Lowicz, Sochaczew, and Kutno. The area o orchards ranged from 4 to 35 ha with the fact that in many households in addition to apple trees cherries and plums were cultivated. Most farms were equipped with BURY WULKAN sprayers although some farm used PILMET Sleza sprayers. Compliance in the opinions of experts was checked in the first place based on the coefficient of variation, whose value for the needs of expert and mathematical method is standardized [7,3]. If the value of the coefficient of variation was less than 0.25 the congruity of ranks appointed by experts was sufficient. For values above those, 0.3 was considered to be low.

Subsequently, the experts congruity was tested with the coefficient of concordance and  $\chi$ -square test [7,3].

In case of the absence of a satisfactory compliance expert opinions the test procedure assumed second stage of the study. At this stage experts who were not convergent in their opinions were informed of the evaluations given by the other experts and asked to respond to them.

### RESULTS

Based on the survey evaluation of 30 factors was obtained. The determined values of the priorities of the system factors and their ranking is shown in Figure 1.

According to the evaluation procedure the parameters were divided into four validity ranges (high - I, higher than average - II, medium - III, lower than average - IV) by setting their "importance / weight" and the average value of the parameter in the interval (table1). "Weight of priorities" indicates the degree of accomplishment of the main target by a group of factors, which was in this



Fig. 1. The values of the priorities of local, III order factors

Range number	Range limits	Labels of factors included in the range	"weight of priorities"	Mean value of system priorities in the range
Ι	8,96-11,37	C 6.1	11,34	11,34
II	6,54-8,95	C 6.2, C 6.3	14,60	7,29
III	4,12-6,53	C 1.4, C 1.5, C 3.2, C 3.3	18,58	4,64
IV	1,7-4,11	C 1.2,C 1.3,C 5.3,C 1.1,C 4.5,C 4.5,C 3.2,C 4.4,C 2.4,C 2.5,C 5.3,C 2.2,C 2.6,C 4.4,C 5.7,C 5.2,C 4.1,C 5.6,C 5.4,C 2.1,C 2.3	55,49	2,64

Table 1. System priorities ranges

3.

4.

interval and is determined by the sum of the system priorities of these factors.

The range of high importance included one single factor marked as C 6.1 i.e. too high purchase price of the sprayer, whose "priority weight" is 11.34%.

The second range has two factors marked with C 6.2 and C 6.3 - high prices of spare parts and high costs of services provided by service departments, whose "priority weight" is 14.60% and the average value of the priorities is 7.29%.

The third range includes four factors whose "priority weight" is 18.58%, while the fourth range has 21 factors with "weight of priorities" of 55.49%. Although the "weight" factors in these ranges is significant, the average factor value in the range is 4.64 and 2.64% only.

### CONCLUSIONS

- 1. The most important factors that affect fruit growers dissatisfaction with the offer of orchard sprayers on the Polish market is too high purchase price of the sprayer, whose "priority weight" is 11.34%.
- 2. With regard to validity of the factors then two factors come: high prices of spare parts and high costs of services provided by service departments, whose "priority weight" is 14.60% and the average value of the priorities is 7.29%.
- Other factors were in the range of average and below average. "Weight of priorities" in these ranges is 18.58% and 55.49%, while the average priority value range is 4.64% and 2.64%, respectively.

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### HIERARCHIA WPŁYWU CZYNNIKÓW TECHNICZNYCH I EKONOMICZNYCH NA STOPIEŃ NIEZADOWOLENIA ROLNIKÓW Z POSIADANYCH OPRYSKIWACZY SADOWNICZYCH

S treszczenie. Istnieje hierarchia technicznych i ekonomicznych czynników wpływających na satysfakcję rolników, którzy posiadają opryskiwacze sadownicze dostępne na rynku w Polsce. Najważniejszymi czynnikami, które powodują niezadowolenie z oferty rynkowej opryskiwaczy są: zbyt wysoka cena zakupu opryskiwacza, za którymi idą wysokie ceny części zamiennych oraz wysokie koszty serwisu.

Słowa kluczowe: opryskiwacz sadowniczy, oceny, hierarchia.

### Change in strength of tomato fruit skin during ripening process

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S u m m a r y. The presented work introduces the results of the various ripeness degrees of Admiro and Encore tomato fruit varieties influence on selected mechanical properties of their skin. There were determined the strength parameters values: Young's modulus, critical compressive stress and Poisson's ratio decreased along with the achievement of full maturity by the examined fruit and were dependent on the tomato variety. Red tomato fruit skin of Encore variety, ripening at 13 °C had a higher value of Young's modulus than the skin of Admiro variety maturing under the same conditions. The highest value of Poisson's ratio was determined for the fruit with the orange-colored peel and achieved 0.73 for Admiro variety and 0.56 for the Encore fruits. The Poisson ratio lowest value, accounting for 0.47, was obtained for the red fruit skin of both cultivars ripening at 21 °C.

Key words: strength properties, tomato fruit skin, the ripening process.

#### INTRODUCTION

A plant material characteristic in terms of its mechanical properties is associated directly with the final product quality [22, 44]. In the case of tomato fruits the key factors deciding about their purchase are color and texture that are usually determined by using the senses but also with the instrumental measurements [6, 29]. Many instrumental methods of destructive and nondestructive character are based on force-deformation-time relationship. Such measurements results define the mechanical properties of the studied objects in terms of force, energy and pressure [12, 42, 55]. Parameters determined in a strength test are also correlated with the plant products rigidity, which being a criterion for assessing their quality and maturity before harvest, is directly related to their growth phase [17, 38]. Mechanical properties and textural characteristics of plant product are also influenced by biophysical and biochemical changes occurring as a result of maturation during storage [39, 41, 47] and devastat-

ing impact of external factors. Delicate plant material is exposed to damage in each phase of production, which is conditioned by the nature of the experienced load [16, 32, 39, 49]. Reducing raw material surface damage and maintaining high quality standards is therefore extremely important in crop production. In the case of tomato glasshouse cultivation, radial and concentric cracking of their skin pose a serious problem. Fruit showing such surface defects is characterized by the reduced shelf life and is not intended for direct consumption [11]. Therefore, the knowledge of the skin mechanical properties is of major importance not only in terms of market product quality and safety, but also for its subsequent storage, processing as well as during designing machines and devices used in manufacturing [46]. The skin of tomato fruits functions mainly as a protection of soft internal tissue against external factors. Peel is involved in growth control [2, 3] and effectively insulates the interior from the outside atmosphere, reducing thereby the gas diffusion process [1, 37, 50] as well as transport of water and other dissolved substances [10, 40, 45]. As the top layer of fruit is exposed to the greatest mechanical damage which size depends on the fruit's physiological condition. The biomechanical properties of tomato fruit skin epidermis, depending on the fruit development stage [4] and changes in the strength parameters during storage at different temperature and humidity conditions [33] were determined throughout the strength tests. Taking into account the different maturity state, tomato fruit shape and surface cracking susceptibility, the mechanical properties of the skin [3, 8, 18] and enzymatically isolated epidermal [3] were also investigated. On the basis of the puncture test carried out on various elements of the tomato fruit's internal structure hardness depending on the skin dyeing degree was determined [26], while in the compression test, among others, cracks on the surface were observed [35]. Furthermore, stiffness, the volume of strain and

force required to puncture the skin were analyzed [46], as well as the strain causing fracture, deformation energy and modulus of elasticity [28].

The aim of this study was to determine Young's modulus, Poisson's ratio and critical compressive stress values by the uniaxial tensile tests application for the tomato fruit skin in a various maturity stages.

### MATERIALS AND METHODS

Laboratory tests were carried out on green tomato fruits of Admiro and Encore varieties, similar in size, supplied by the Leonów Greenhouse Gardening Company in Niemce near Lublin.

The experiment was conducted on the measuring position assigned for the determination of mechanical properties of biological material [20].

Young's modulus, Poisson's ratio and critical compressive stress values were determined with the use of uniaxial tensile test. Collected from the parent plant green tomato fruits were placed in a climatic chamber at two temperatures: 13 °C and 21 °C ( $\pm$  1 °C) making the need for the process of their maturation in the assumed temperature conditions. Polish Standard (1993) recommends storing tomato fruit in early dyeing stage at a temperature of 13 °C while the temperature of 21 °C simulates the natural retail and storage conditions [36].

First measurements were performed immediately after green tomato fruits were harvested and the next when their skin dyed entirely in the orange color. The study were completed at the time when the skin of fruits stored at 13 °C and 21 °C received a red color, after 28 and 12 days of storage respectively, at the assumed temperature conditions. Tomatoes were removed from the controlled environment chamber and kept in a laboratory until fruit temperature became equal to the ambient temperature. After washing and drying the fruit surface, skin specimens in the form of longitudinal strips were procured for tensile tests. The incisions were made with a profiled, single-blade knife with a limiter. Parameters such as length, width and thickness were measured before the examination.

Samples were cut from the meridional part of the fruit and had the shape of a strip with the length of 30 mm  $\pm$  0.1 mm and the width of 10 mm  $\pm$  0.1 mm. Mentioned values were measured with the use of the caliper. Thickness of each sample was measured under an optical microscope at 5 points in the central part of the strip on both sides. Thickness measurement, which was an average of 10 individual measurements, was performed with the accuracy of  $\pm$  0.05 mm.

Prepared samples were placed in clamping grips of the tensile machine, which allows constant and measurable tensile force value increase. Powdered graphite markers were randomly sprayed on the sample surface.

The method of random markers was applied to determine Young's modulus and Poisson's ratio of the tomato's fruit skin. Mentioned method relies on the image analysis and the distance between points on the sample, subjected to uniaxial stretching tests, surface [19].



Fig. 1. Example of a dependence  $\epsilon_{_{x}}(\sigma)$  and  $\epsilon_{_{y}}(\sigma)$  for the stretched specimen

The main advantage of this method is that obtained results are independent of the effects observed along the specimen's edges which are close to the clamping grips of the testing machine. The random markers method allows measurements at well-defined location of the skin segment, even in case of partial damage. An additional benefit is the possibility to observe a permanent increase in strength rather than strain [19].

Each measurement series was performed in 30 replications. Young's modulus value for each sample was determined basing on the value of the straight line slope which approximated individual dependence  $\varepsilon_x = f(\sigma)$ (Fig. 1), where  $\varepsilon_x$  is the relative elongation in the direction of the x-axis (-), and  $\sigma$  is the value of stress (MPa).

The critical surface tension of stretched specimen was determined using eq. (1), and Poisson's ratio v was computed basing on dependence (2):

$$\sigma_k = \frac{F_z}{S},\tag{1}$$

$$v = -\frac{\varepsilon_y}{\varepsilon_x},\tag{2}$$

where:  $F_z$  – force maximum value corresponding to destruction of a sample,

S - cross-sectional area,

 $\varepsilon_x$  – relative elongation in the direction of the applied tensile force *F*,

 $\varepsilon_y$  – relative elongation in a perpendicular direction to the applied force *F*.

The total values of Young's modulus, Poisson's ratio and the critical compression stress were the averages of all individual measurements.

### RESULTS AND DISSCUSSION

Conducted research indicates that the skin of tomato fruit shows no tendency to increase in strength. It was

		The tomato sk	in surface dyeing	degree	
	Variety	Green fruits	Orange fruits	Red fruits ripening at 13 °C	Red fruits ripening at 21 °C
Vounc's modulus E [MDs]	Admiro	4.3	4.15	2.48	2.25
roung s modulus E [MPa]	Encore	5.55	5.94	4.19	2.98
Deisson's motio u []	Admiro	0.68	0.73	0.57	0.47
	Encore	0.51	0.56	0.43	0.47
Critical community attacks - [MDa]	Admiro	0.21	0.29	0.19	0.19
Critical compressive stress $\sigma_k$ [MPa]	Encore	0.48	0.49	0.36	0.18

Table 1. The average values of strength parameters determined in the study

noted that with the ongoing maturation process skin becomes more fragile and susceptible to damage. Table 1 shows determined for tomato peel of both varieties being in various maturity stages, average values of Young's modulus, Poisson's ratio and critical compressive stress.



Fig. 2. The average values of Young's modulus E along with standard deviation determined for the skin of Admiro and Encore varieties in various stages of maturity. I - green fruits, II - orange fruits, III - red fruit maturing at 13 °C, IV - red fruit maturing at 21 °C

The value of Young's modulus decreased with the ongoing process of fruit ripening (Fig. 2). In the case of Admiro variety skin, 42 % reduction in modulus of elasticity for red fruits ripening at 13 °C compared to the value of Young's modulus determined for the skin of green fruits was observed.

Approximately 48 % lowering in the value of E was noticed for red fruits of mentioned variety, ripening at 21 °C in relation to the green fruits. Skin of Encore variety ripening at 13°C achieved Young's modulus value by 25 % lower (4.19 MPa) than modulus calculated for green fruit skin (5.55 MPa), while for fruit ripening at 21 °C more than 46 % decrease in E value was received in comparison with values received for green fruits. Red fruit maturing at 13 °C had a higher Young's modulus than those ripening at 21 °C [8, 18]. A greater difference in E values within this group of fruits, accounting for 1.21 MPa, was observed for the Encore variety while for Admiro it reached only 0.23 MPa.

Analysis of available literature proves a strong dependence of Young's modulus values determined for tomato fruit skin on the variety [2, 3, 4, 23, 24, 34, 52]. Such large variations of this parameter may indicate differences in the cellular structure of the skin and different strength properties.



Fig. 3. The average values of Poisson's ratio v along with standard deviation determined for the skin of Admiro and Encore varieties in various stages of maturity. I - green fruits, II - orange fruits, III - red fruit maturing at 13 °C, IV - red fruit maturing at 21 °C

The varying maturity degrees of tomato fruit differentiate the value of Poisson's ratio (Fig. 3).

Value of Poisson's ratio for green fruit was less than in case of orange-colored skin, for which the highest value amounting to 0.73 was determined towards Admiro variety. Skin of Encore cultivar in the same state of ripeness was characterized by the Poisson's ratio value equal to 0.56 (Fig. 3). Significantly higher values of the vcoefficient were determined for Admiro variety, however in the case of green fruits of both cultivars ripening at 21 °C the coefficient reached 0.47 [30].

Literature data indicates that the skin of examined tomato fruit cultivars was characterized by similar values of Poisson's ratio as the skin of apples [9, 21], onions [48] and broad beans [19].

The theory of elasticity [31] for isotropic 3D systems precludes the existence of materials, for which Poisson's ratio v exceed the value of 0.5. Using this theory, the v dependence on the degree of tested object isotropic dimension could be obtained [54]:

$$-1 \le v \le \frac{1}{D-1}.$$
(3)

For isotropic three-dimensional objects (D = 3) Poisson's ratio v:

$$-1 \le \nu \le \frac{1}{2}.\tag{4}$$

However, for very thin or two-dimensional (D = 2) isotropic objects mentioned constraints change:

$$-1 \le v \le 1. \tag{5}$$

It should be remembered that as certain restrictions are applied only to isotropic objects. For anisotropic materials, Poisson's ratio v can greatly exceed the limits defined by equations (4) and (5). In the theory of elasticity [5] Poisson's ratio is defined as the negative value of the deformation  $\varepsilon_y$  in a direction perpendicular to the direction of the stretching force divided by the value of the deformation  $\varepsilon_x$  in the direction consistent with the force direction. Since proposed method allows experimental determining of both:  $\varepsilon_x$  and  $\varepsilon_y$  values, there are no contraindications to use the name of Poisson's ratio, even when v > 1 [53]. Obviously using other expressions of elasticity in the case when they refer to a material with Poisson ratio v > 1 should be done very cautiously.



**Fig. 4.** The average values of critical compressive stress  $\sigma_k$  values along with standard deviation determined for the skin of Admiro and Encore varieties in various stages of maturity. I - green fruits, II - orange fruits, III - red fruit maturing at 13 °C, IV - red fruit maturing at 21 °C

As previously mentioned Poisson's ratio values significantly above 0.5 were observed in the different anisotropic materials, also including biological [13, 51].

For the green and orange tomato skin of Admiro and Encore varieties as well as for Admiro cultivar peel, maturing at 13 °C, Poisson's ratio was higher than 0.5 (Table 1), which means that exceeded the usually taken as a limit value for isotropic biological materials [7, 14, 43, 54]. In other cases, the value of this ratio ranged from 0.43 to 0.47. Examples of plant materials for which the value of Poisson's ratio was higher than 0.5 might be find in literature, for example for potato tissue [15], soybean hypocotyl [25], the maize root [27] and beans covers [19].

Figure 4 presents the average values of the critical compressive stress determined for examined tomato cul-

tivars skin. With the fruits maturity increase, which was characterized by the skin red color, the critical compressive stress value decline was observed.

Encore variety tomato fruit skin was characterized by larger values of critical compressive stress in comparison to Admiro cultivar. In the case of red fruits of Encore variety ripening at 21 °C, over 62 % lower value of critical compressive stress than in case of green fruit of this cultivar was observed. For Admiro tomatoes, in contrast,  $\sigma_{i}$  depreciation amounted to only 10 %.

### CONCLUSIONS

- The strength parameters were determined: Young's modulus, Poisson's ratio and the critical compressive stress values decreased along with fruit maturity process. Green fruit skin of both cultivars was characterized by higher values of Young's modulus than the one determined for the skin of red fruits ripening at 13 °C and 21 °C.
- The Young's modulus value depends on the tomato variety. Red fruit skin of Encore variety maturing at 13 °C had a higher Young's modulus value than the skin of Admiro fruits ripening under the same conditions.
- 3. The highest value of Poisson's ratio was determined for the orange-colored skin and amounted to 0.73 for Admiro and 0.56 for Encore cultivar. The lowest value of this coefficient of 0.47 was obtained for the red fruits skin of both cultivars ripening at 21 °C.
- 4. The critical compressive stress value determined for the skin of both tomato cultivars decreased along with achieving full maturity.
- 5. Ripening temperature had a dominant influence on the rate of skin dyeing. Fruits ripening at 21 °C after 12 days of storage in a climate chamber were completely stained, while those maturing at 13 °C to achieve comparable state required 4 weeks of storage.

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### ZMIANA WYTRZYMAŁOSCI SKÓRKI OWOCÓW POMIDORA W TRAKCIE ICH DOJRZEWANIA

S treszczenie. W pracy zaprezentowano wyniki badań wpływu różnego stopnia dojrzałości owoców pomidora odmian Admiro i Encore na wybrane mechaniczne właściwości ich skórki. Wartości wyznaczanych parametrów wytrzymałościowych: modułu Younga, współczynnika Poissona oraz naprężenia krytycznego malały wraz z osiąganiem przez owoce stanu pełnej dojrzałości i były uzależnione od odmiany pomidora.

Skórka czerwonych owoców pomidora odmiany Encore dojrzewających w temperaturze 13 °C miała wyższą wartość modułu Younga niż skórka owoców odmiany Admiro dojrzewających w takich samych warunkach. Najwyższą wartość współczynnika Poissona wyznaczono dla owoców o pomarańczowej barwie skórki i wynosiła ona 0,73 dla odmiany Admiro i 0,56 dla odmiany Encore. Najniższą wartość współczynnika Poissona wynoszącą 0,47 uzyskano dla skórki czerwonych owoców obu badanych odmian dojrzewających w temperaturze 21 °C.

Słowa kluczowe: właściwości wytrzymałościowe, skórka owocu pomidora, proces dojrzewania.

# Assumptions for collecting information for a module concerning a machinery park of ecological farms in GEKKO programme<sup>1</sup>

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Summary. The work presents an analysis of the machinery park equipment in the group of 100 ecological farms. It was one of the starting points to undertake an attempt of working out a module, in a computer programme concerning a machinery park in ecological farms. Works on the module have been carried out also based on consultations with ecological agriculture experts. The obtained research results and the authors' experience gained at the study on the programme allow for the conclusion that the worked out module can be used in practice and can facilitate the work of advisers, inspectors and representatives of other units which supervise and cooperate with the producers with ecological food. Moreover, it will indirectly influence the growth of efficiency of the carried out agricultural production.

Key words: computer program, machinery park, ecological farms.

### INTRODUCTION

Ecological farming means "the system of farming, which activates natural environment production mechanisms through application of natural, technologically nonprocessed means, and at the same time ensures durable soil fertility and animal health as well as high biological quality of agricultural products" [7]. The Polish market of ecological products is characterised by slow but systematic increase of the number of farms producing food in this system and at the same time the increase of the offer scale. Poland has very good natural and social conditions for ecological farming development. A superior participation of family agricultural farms, usually of multi-directional production, which easily transform into farms producing healthy food are a very significant factor of this development. Moreover, factors such as low environmental pollution, big surface area of the protected

terrains, low level of chemical crop boosting substances use, multi-directional character of production of agricultural farms and high resources of free and considerably cheap work force in agriculture, positively influence the development of ecological production in Poland.

Present and future development of agricultural farming is strictly connected with its competitiveness towards other agricultural systems. Streamlining of activities in agriculture, consisting in, inter alia, the best use of the equipment used in agricultural production, also requires the knowledge on the shaping factors of the machinery and the tractors exploitation process in a farm, which according to Kocira and Parafiniuk [4] significantly influences efficiency of farming. Proper organisation of transport has a significant meaning from the plant production point of view through the optimal selection of transport means [5, 6]. Many authors indicate legitimacy of using modern information technologies supporting efficient agricultural production [1, 2, 3, 9]. The research they have carried out shows the need for implementation of computer systems in different fields of activity concerning agricultural production, inter alia, for managing of a widely understood agricultural information, optimisation of agricultural production and achieving required quality indexes of food products. The required reporting which accompanies ecological agricultural production is a basic condition for obtaining the available union subsidies in this scope [8]. At the same time, agriculture is also an area where implementation of IT systems may activate agricultural environment to use modern tools supporting management. Therefore, it is significant to know the problems of ecological farms functioning, monitor their activity and indicate the activities which would allow for an increase of their competitiveness.

<sup>&</sup>lt;sup>1</sup> The work was carried out within development grand NO. 12 0165 10 titled: "Innovative influence of technology and information management supporting system on the production efficiency in ecological farms"

### **OBJECTIVE AND THE SCOPE**

In the age of information it is hard to imagine a well operating system of food production without using an electronic calculation technique, which would determine the assumptions, rules of operation as well as complex and fast evaluation of the economic activity of agricultural units producing ecological food in an organised way.

Presently, ecological farm owners meet considerable difficulties at keeping detailed production documentation as a statutory requirement. GEKKO programme is dedicated to support reporting with the use of a computer. Considering farmers' needs, an attempt was taken up to form the assumptions which will be used to form a module collecting information on a machinery park of ecological farms. The module, upon being designed and included in the programme, will allow for the support of rational machinery park management.

### RESEARCH AND INITIAL ANALYSIS RESULTS

Many authors consider ecological farms as extensive, weakly equipped and using low-advanced production technologies. Providing that an extensive character can be explained by conditions resulting from ecological production rules, technical equipment frequently does not differ from conventional farms operating in comparable conditions (natural conditions, surface area of a farm, region of activity). As a result, production technologies are not less advanced than in conventional farms. Necessity of limiting the use of chemical substances may cause necessity of frequent agrotechnical operations, inter alia, mechanical weed destruction. This, in turn influences the need to purchase modern machines. Table 1 presents machinery park equipment of ecological farms covered by the research within grant NO 12 016510. The data included in the table concern the results obtained in the initial research on 100 ecological farms on the territory of south Poland. These facilities were divided into 8 area groups. The analysed objects involved on average 1.58 tractors per one farm, and this value was not lower than one in any of these groups. From among the listed group of machines, cultivating machines were the most numerous - in each area group more than 2 units per farm. The machines for green forage harvesting were also numerous. High level of machinery park equipment at the investigated farms with green forage harvesting machines results directly from the structure of use of this facilities, where extensive production based on meadows and pastures was carried out many times. Among the studied farms, there was also a group of 20 farms designed for milk production, where green forage and hay are the basic fodder. Moreover, they have to apply to ecological farming rules i.e. cattle grazing. In the evaluated population, fertilization, protection and plant care machines constituted a substantial group. It results from the fact that guidelines concerning the rules of using those

machines in ecological farms disable the use of machines from these groups in ecological and conventional farms at the same time. Therefore, farmers, whose use of services is limited (using equipment in conventional farms), are forced to purchase this type of a machine (Table 1).

In the case of the remaining listed group of functional machines, their number is satisfactory. Although, the quantity analysis indicates considerably good technical equipment, one should remember that in majority these are old and worn out machines of parameters far too different from modern standards. It is caused by goods production of ecological farms which is lower than in conventional farms and at the same time by lower incomes, which influence their low investment potential even upon considering a fund. As a consequence, majority of ecological farms can not afford to purchase modern machines. It concerns mainly farms of a small surface area. Therefore, considering the necessity of applying modern technologies connected with a low investment potential of farms, proper machinery work organisation and the rational use of the possessed machines gets a new meaning. Specialistic computer programmes can play a significant role in rational management of a machinery park.

Farmers obliged to keep reports of the production, which they carry out in the ecological system, may use presently GEKKO programme. Originally, this programme includes statutory guidelines and requirements of supervising units concerning agricultural machines and mechanisation. Developing this programme with a module that collects information on the machinery park, will allow support of the rational machinery park management. As a result, a farmer using a reporting programme will gain additional tool informing him on a present state and indicating directions of organisation activities which allow obtaining indexes characterising effective use of the machinery park.

GEKKO programme in its basic application is designed to simplify keeping the reports in ecological farms, which is required by the supervising institutions. However, application of the programme for this purpose, does not exclude its other applications, inter alia, calculations concerning efficiency of the used mechanisation. In this situation, widening the functionality of application with a module concerning agricultural engineering is well grounded.

Preparing guidelines, which may serve for working out a module collecting data concerning a machinery park in GEKKO programme, was carried out in four stages:

### 1. THE ANALYSIS OF INFORMATION REQUIRED BY INSTITUTIONS, LISTED WITH INFORMATION RECOMMENDED BY EXPERTS.

The scope of data required by binding law and supervising institutions, concentrates as a rule on areas which are not connected with mechanisation. In principle, the required documentation does not include any information concerning machines which farmers possess. Only in the registry of agrotechnical activities, a farmer should list field works technologies which are used in a farm.

farms
nvestigated
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Description
1.
Table

			Area groups								
Specificatio	-	Parameter	up to 3 ha	3.01 to 5 ha	5.01 to 7 ha	7.01 to 10 ha	10.01 to 15 ha	15.01 to 20 ha	20.01 to 40 ha	surface area 40 ha	Total
			Average	Average	Average	Average	Average	Average	Average	Average	Average
		unit-farm <sup>-1</sup>	1.29	1.43	1.44	1.13	1.86	2.13	1.78	2.67	1.58
Number of 1	ractors	unit·ha <sup>-1</sup> AL	0.69	0.39	0.26	0.14	0.15	0.12	0.07	0.05	0.27
		unit-farm <sup>-1</sup>	0.12	0.07	0.06	0.19	ı	0.13	1	0.5	0.11
guit'	Irucks and delivery trucks	unit·ha <sup>-1</sup> AL	0.09	0.02	0.01	0.02	1	0.01		0.01	0.03
sueə odsu	F	unit·farm <sup>-1</sup>	0.88	1.07	1.13	0.94	1.29	1.38	1.33	2	1.16
ert fo m gn	Kemaining transport means	unit·ha <sup>-1</sup> AL	0.45	0.29	0.2	0.11	0.1	0.08	0.06	0.04	0.2
load		unit·farm <sup>-1</sup>	0.18		0.06	1		1	1	0.17	0.05
nN bus	Loading and unioading devices and machines	unit·ha <sup>-1</sup> AL	0.07		0.01	1		1	1	0.003	0.01
		unit-farm <sup>-1</sup>	2.88	3.5	3.88	2.81	2.64	3.13	2.78	4.33	3.18
	Cultivating machines	unit·ha <sup>-1</sup> AL	1.41	0.92	0.69	0.33	0.21	0.17	0.11	0.08	0.59
	Fertilization, protection	unit-farm <sup>-1</sup>	2.06	2.14	3.06	1.31	2.57	3.63	2.44	2.67	2.38
	and plant care machines	unit•ha <sup>-1</sup> AL	1.03	0.57	0.53	0,16	0.2	0.2	60.0	0.05	0.42
		unit-farm <sup>-1</sup>	0.76	1.29	1.38	0.81	1,57	1.13	1.11	1	1.13
	Sowing and planting machines	unit·ha <sup>-1</sup> AL	0.34	0.34	0,24	0.1	0.13	0.07	0.04	0.02	0.19
		unit·farm <sup>-1</sup>	2.18	1.79	2.13	1.63	3.5	3.25	n	3.33	2.44
5	Green Iorage narvesting machines	unit·ha <sup>-1</sup> AL	1.11	0.51	0.37	0.2	0.27	0.18	0.12	0.06	0.42
sənida		unit·farm <sup>-1</sup>	0.65	0.86	0.81	0.75	0.71	0.63	0.89	1	0.77
oem f	Grams and root crop harvesting machines	unit·ha <sup>-1</sup> AL	0.31	0.25	0.14	0.09	0.06	0.04	0.04	0.02	0.14
o dno		unit-farm <sup>-1</sup>	0.59	1.07	0.69	0.63	1.93	2	1.56	1	1.09
al gro	Animal production machines	unit·ha <sup>-1</sup> AL	0.24	0.31	0,11	0.08	0.15	0.11	0.06	0.02	0.15
noitoi	o service s	unit·farm <sup>-1</sup>	0.41	0.86	0.56	0.44		0.38	0.22		0.4
ung	seeds cleaning and sorting machines	unit·ha <sup>-1</sup> AL	0.18	0.21	0.1	0.05	1	0.02	0.01	I	0.09

However, there is no information in the forms concerning the machines which have been used, and in original forms their use may be listed in additional notices. This system causes that farmers do not enter information which is note required (including machines) and additionally list only activities and agrotechnical operations, which in their opinion may be essential from the point of view of ecology rules (basically they confirm, that the applied technologies are ecological).

Consultations concerning functionality of GEKKO application were carried out many times with experts, i.e. farmers, advisers, inspectors supervising ecological farms, employees of licensing units and scientists. During consultation, introduction of a larger number of the collected data on the machinery park was suggested. At the beginning the method of using these data was not specified. However, it was soon determined that these data may be used inter alia in the process of preparing subsidy applications (not necessarily connected directly with ecological production) and for obtaining information on using and operational costs of the possessed equipment. Although, in the initial stage, it was assumed that because of the programme use simplification, it will collect only a minimal scope of data, the authors found it purposeful that a developed version of application for experts should be designed. A module concerning mechanisation will be one of these modules.

2. DETERMINATION OF THE SCOPE OF INFORMATION CONCERNING MECHANISATION AND TECHNICAL MEANS OF PRODUCTION COLLECTED IN GEKKO PROGRAMME IN THE PRESENT VERSION.

Although, a current documentation of ecological farms operation does not require information concerning a machinery park, information on agricultural machinery and their use in technologies has been already anticipated in the basic version of GEKKO programme. Fig. 1 presents a fragment of a data base of this programme concerning the machinery park and Fig. 2 presents an exemplary screen shot.



**Fig. 1.** A fragment of a GEKKO programme data base concerning the machinery park (relation scheme, basic version)



Fig. 2. An exemplary screen shot of GEKKO programme (actions module)

This information includes the name of the machine, type and the year of production. Additionally, in the table of activities, efficiency of a particular activity may be entered and in table 2 under the "Use Machine" key word, all applied machines and tractors can be listed. As a result of entering data concerning the machine and information included in the "Field Register" table, which constitutes an equivalent of the record of agrotechnical activities, one may obtain information on:

- farm equipment with tractors and agricultural machines,
- age of the owned equipment,
- machines used in particular technologies.
   Additionally, the following may be calculated:
- number of machines and tractors of particular types,
- their real use,
- dates on which they operate.

An exemplary screen shot of GEKKO programme was presented in Fig. 2.

### 3. DETERMINATION OF THE SCOPE OF INFORMATION INDICATED FOR BEING INCLUDED IN THE MODULE WHICH IS BEING DESIGNED.

This part of analysis is designed to concern the scope of the introduced data. However, their scope has to be subordinated to a final effect. Taking the above into consideration firstly, a minimal scope of information, which has to be obtained at the programme output, should be determined.

As a result of consultation, it was assumed, that the programme, which concerns the use of the machine should give an opportunity to list their:

- use,
- dates, when they are used,
- exploitation period,
- operation costs,
- replacement and current value (upon deducting appreciation charge),
- exploitation period,
- replacement value of a machinery park.

A part of the above mentioned indexes may be calculated as soon as after entering complex data in the standard version. The remaining has to be included in the designed module. Whereas, the scope of additional data may be divided into two parts:

- the one concerning a specific machine (which basically has to be entered by a farmer) and
- the typical one for the group of machines (which may be downloaded from a built-in data base).

This division is crucial from the point of view of ergonomics of the programme use, since it enables the decrease of amount of data entered by the programme user. This effect is obtained through placing these data in the built-in data base or downloading from outer sources. However, it should be mentioned that, although there are indexes typical for the group of machines, in special cases they have to be treated separately for particular machines. Therefore, the programme has to enable entering a particular index for a single machine, although the index for a group has a different value.

As a consequence, it has been determined, that entering the following data to the programme is necessary:

- machine price (or its replacement value),
- maximum exploitation period,
- operation potential (the amount of work, which the machine can use in the exploitation period),
- surface area taken by a machine,
- efficiency,
- power or power demand,
- type and unit fuel consumption,
- cumulated coefficient of repairs and technical service,
- annual insurance costs,
- type and unit consumption of additional materials,
- number of personnel,
- energy mean cooperating with a machine,
- others e.g. load capacity, mass, volume, etc. or other data which are specific for a particular group of machines. Diversity of parameters causes that it is difficult to predict all possibilities on the stage of the programme design.

The above data, entered to the system, upon application of suitable algorithms, will allow calculation of the assumed indexes.

4. THE METHOD OF IMPLEMENTATION OF ADDITIONAL INFORMATION IN THE PROGRAMME - INSTRUCTIONS FOR MODULE CONSTRUCTION.

The method of implementation in the programme has to concern, first of all, two areas, which has to be considered by programmers at working out a module. Data, which have to be collected in order to enable further calculations, constitute the first area, whereas algorithms and methods of indexes calculations which result from the module operation are the other area. In the study herein, the authors concentrated on the first area. It is justified by the fact, that collection of proper data may enable calculation of further indexes in the future, even these, which can not be predicted on this stage. Additionally, it has to be mentioned that the data collected today may enable future calculations. Whereas, lack of proper input information may effectively disable even basic calculations. Fig. 3 presents a fragment of a data base of GEKKO programme concerning a machinery park in the version extended with additional elements.

When analysing data placed in the scheme (Fig. 3) one may notice that as a result of the suggested modifications only two tables will be modified: "Machines" (including data of machines in a farm) and "Machine type" (concerning machine types - universal data). Such a small integration in a developed structure of a full data base of the programme, including few dozens of tables (53 composing tables in the 0.45 version of the programme) is advantageous. However, it may happen that the scope of changes will be bigger in the final version.



Fig. 3. A fragment of a GEKKO programme data base concerning a machinery park (relation scheme, extended version)

A correct design of a data base will result in a possibility of entering new procedures of calculations in the programme using existing data.

### SUMMARY

Ecological farming, despite differences from conventional farming does not diverge from the accepted standards within the scope of the machinery park. Since, also in this case, a proper mechanisation of both plant and animal production conditions effective farming. The initial research, which was carried out within the research project, proved that quantity equipment of the machinery park in the researched farms is on the satisfactory level and allows mechanising particular agro-technical operations. However, frequently the only fact of possessing machines gives no bases for effective use. Thus, only the rational and planned use is a condition of profitability of their exploitation. In this aspect, the problem of planning and recording activities concerning the scope of the machinery park use appears. In the case of ecological farming, farmers meet the necessity of keeping reports in the moment of starting their agricultural activity in the system of healthy food production. Upon getting acquainted with the required reporting and consultations with experts on ecological farming, the authors attempted to prepare a module for registration of activities concerning a machinery park while working out a computer programme. Expanding the programme with this module is a result of cooperation with agricultural advisers, who indicated "the usefulness" of operating the data concerning agricultural machines. They frequently make use of this information while preparing applications e.g. concerning purchase of agricultural machines within particular operations of the Development of Country and Rural Areas Programme. In these operations, to justify a specific purchase, a state of the present equipment of the machinery park and inter alia possibilities of using a machine, the purchase of which is intended must be listed.

In the case of ecological farming, farmers who keep a record of activities using the worked-out computer programme will be able to assign the used machines and tools to the activity, apart from the recording of the activity. In effect, the designed module will become a perfect tool, which will influence the evaluation of the technical base use. As a consequence, it will influence the increase of efficiency of the farm management process.

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### ZAŁOŻENIA DLA ZBIERANIA INFORMACJI DO MODUŁU DOTYCZĄCEGO PARKU MASZYNOWEGO GOSPODARSTW EKOLOGICZNYCH W PROGRAMIE GEKKO

Streszczenie. W pracy przedstawiono analizę wyposażenia parku maszynowego w grupie 100 gospodarstw ekologicznych. Był to jeden z punktów wyjścia do podjęcia próby wypracowania modułu w programie komputerowym dotyczącego parku maszynowego w gospodarstwach ekologicznych. Prace nad modułem zostały przeprowadzone również w oparciu o konsultacje z ekspertami rolnictwa ekologicznego. Uzyskane wyniki badań i doświadczenia autorów zdobyte w pracy nad programem pozwalają na wniosek, że opracowany moduł może być stosowany w praktyce i może ułatwić pracę doradców, inspektorów i przedstawicieli innych jednostek, które nadzorują i współpracują z producentami żywności ekologicznej. Ponadto, wpłynie to pośrednio na wzrost wydajności produkcji rolnej.

Słowa kluczowe: program komputerowy, park maszynowy, gospodarstwa ekologiczne

# The possibilities of using linear models in the automation of agricultural machinery driving

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Summary: As a result of developing computer technology very complex, nonlinear models of vehicles have started to appear. But an important disadvantage of a model with high degree of freedom is a great deal of data needed to describe the vehicle features. It is especially important while the model is being adapted to use at a preliminary design stage, when many data lack. Lacking and uncertain data decrease accuracy of results obtained by simulation and put usefulness of expenditure of work connected with the model building in question. The paper presents the possibility of using simple linear models of agricultural transport units in the systems supporting the work of the driver. Two different models were analyzed. The first is the structural model with two degrees of freedom, and the second model uses transmittance functions. The results obtained by computer simulation and by measurements were compared. The concept of the system using such models was presented.

K e y w o r d s : agricultural machine, modeling, simulation, driver support.

### INTRODUCTION

As a result of developing computer technology very complex, nonlinear models of vehicles have started to appear. But an important disadvantage of a model with high degree of freedom is a great deal of data needed to describe the vehicle features. It is especially important while the model is being adapted to use at a preliminary design stage, when many data lack. Lacking and uncertain data decrease accuracy of results obtained by simulation and put usefulness of expenditure of work connected with the model building in question. For such a case we made an attempt of using a comparatively simple model with little degree of freedom [].

The systems supporting a driver's work in an agricultural vehicle have a few basic functions. The relief operator's continuous monitoring and making correction of drive direction in addition to the controlling function of an agricultural machine is the most important [].

Realization of the tasks can be provided by appropriate controllers allowing for the keeping of a vehicle motion's stability and realization of this motion's assumed direction.[, ].

A typical example of an agricultural vehicle is a water cart for transporting liquid waste (Fig. 1). There are issues connected with the behavior of the vehicle when it is driven on any curve. Due to the fact that the tractors currently can reach speed of  $18 \text{ m s}^{-1}$  (65 km/h), we should, in the kinematics of the whole system, take into account the lateral dynamic susceptibility of the front and rear suspension [].

However, it is the most convenient to consider the issue of impact of the suspension stiffness using an example of the widely-used in agriculture delivery vehicle [, ]. An example is the Mitsubishi L200 (Fig. 2) in combination with a trailer. An important argument in favor of adopting it for the investigation is defining its stability by the standards. You can name here at least basic standards such as ISO 4138, ISO TR3888, ISO 6597, ISO 7975, ISO 9816, ISO 7401 and ISO 12021. For agricultural vehicles such standards have not been developedas yet, hence our interest in the set of car - trailer.

Dynamics and kinematics of the tested vehicle is presented in Fig. 3. It should be noted that on the diagram there is no semitrailer. It was introduced in order to obtain more clarity of motion equations and their analysis.

### EQUATIONS OF MOTION

The basic equations of motion were derived after the adoption of the assumption that the transverse stiffness of the front and rear suspension obtained in the identifica-



Fig. 1. Diagram of dynamics and kinematics of a tractor



Fig. 2. The test object - Mitsubishi L200 car with trailer



Fig 3. Diagram of dynamics and kinematics of the car Mitsubishi L200

tion process are included in tire stiffness [, ]. Thus, for the presented scheme of dynamic and kinematic they can be written in the form of linear differential equations:

$$\begin{bmatrix} \ddot{\psi} \\ \beta \end{bmatrix} = \begin{bmatrix} -\frac{K_{\delta 1}a^2 + K_{\delta 2}b^2}{I_{zz}v_s} & -\frac{K_{\delta 1}a - K_{\delta 2}b}{I_{zz}}\\ -\frac{mv_s^2 + K_{\delta 1}a - K_{\delta 2}b}{mv_s^2} & -\frac{K_{\delta 1} + K_{\delta 2}}{mv_s} \end{bmatrix} \begin{bmatrix} \dot{\psi} \\ \beta \end{bmatrix} + \begin{bmatrix} \frac{K_{\delta 1}a}{I_{zz}}\\ \frac{K_{\delta 1}}{mv_s} \end{bmatrix} \begin{bmatrix} \delta \end{bmatrix}, \quad (1)$$

- *a* distance of the front axle of the vehicle from its center of gravity,
- *b* distance of the rear axle of the vehicle from its center of gravity,
- $K_{\delta l}, K_{\delta 2}$  cornering coefficients of vehicle tyres,
- m mass of the vehicle,

 $v_{s}$  - vehicle speed,

- $I_{zz}$  moment of inertia at the Z axis,
- $\overline{\Psi}$  yaw angle of the vehicle,
- $\beta$  drifting angle of the vehicle.

The identification of the lateral stiffness of the front and rear suspension was performed using the measurements during double lane change meneuver and driving in a circle []. Parametric identification was carried out to find the values of the parameters listed above, which would ensure compliance variables, obtained from the model and measurement results. The function describing the estimation error was non-negative function of estimated parameters [, ,].

### COMPUTER SIMULATION

To validate the model we adopted the path in accordance with ISO TR3888 (Fig. 4), for which the forcing is shown in Fig. 5.

After the identification of the model, series of measurements of set car with semitrailer parameters during the driving were made. The obtained results were compared with the results from computer simulation. Based on the results, as illustrated in Fig. 6 and Fig. 7, we can conclude that the used model correctly predicts the behavior of the vehicle on the road.

Another type of linear models that can be used to describe the behavior of sets of agricultural vehicles are models using transmittance functions. Figure 8 shows a diagram of such a model taking into account the effect of the driver activity.



Fig. 4. Motion paths for the study of the vehicle behaviour during double lane change - ISO TR38888 []



Fig. 5. Steered wheel angle  $\delta$  recorded during the maneuver of double lane change



Fig. 6. Angular velocity of the vehicle deviation obtained from measurements and simulation



Fig. 7. Drift angle  $\beta$  of the vehicle obtained from measurements and simulation



Fig. 8. Block diagram of the linear model using transmittance functions (in Matlab Simulink)

The transfer function can take into account some parameters of driving characteristics such as driving time delay with the aid of, for example, Pade aproximation [, ]. The model can be used then for the analysis of a driver 's behaviour in the function of a driver's effort [, ].

After identifying the transfer function the model allows to get high compatibility between the results obtained from measurements and from simulation (Fig. 9 and Fig. 10).

### THE CONCEPT OF CONTROL OF THE VEHICLES

Fig. 11 shows the scheme of control of the vehicle in which signals from the sensors [] are used to correct the car trajectory. The sensors are used to enable the obtainment of data on the actual position of the vehicle. The block named "Guidance system", based on predictive simulation, generates steering angle  $\delta$  of the wheels.



Fig 9. Y coordinate of the trajectory obtained from simulation using a block diagram of Fig. 8 and from the measurement



Fig. 10. The course of the angular velocity of deflection angle  $\psi$  obtained from simulation using a block diagram of Fig. 8 and from the test

It is implemented by means of hydraulic or mechanical device installed in the vehicle (block Controller on Fig. 11). The response of the vehicle to change of the angle  $\delta$  depends on the properties of the vehicle (Vehicle Dynamics block). Based on the values of the lateral deflection y and the angle  $\Psi$  (Fig. 13), lateral deviation of the vehicle in the vehicle reference point (indicated in Fig. 13 as C) is calculated (L is the distance between the axles of the vehicle) [].

Guidance block is presented in detail in Fig. 12. Steering angle  $\delta$  is calculated on the basis of the current vehicle position relative to the set path (angle  $\Phi$  on Fig. 13) [], data describing the state of the vehicle (speed, acceleration) obtained from the sensors and the linear model of the vehicle [].

### THE CONCLUSIONS

Based on computer simulations it can be accepted that the two presented linear models meet the conditions of conformity with the test results:

- the deterministic flat model with two degrees of freedom,
- the stochastic model based on the identified functions of transmittance.

This suggests that such models can be used in the study of motion and stability in systems supporting the driver's work in agricultural vehicles as well as the driver's behaviour.

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Fig 11. Scheme of vehicle control



Fig. 12. Diagram of block of vehicle control



Fig. 13. The pure pursuit method of calculating the vehicle position relative to a point lying on the trajectory []

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### MOŻLIWOŚCI ZASTOSOWANIA MODELI LINIOWYCH W AUTOMATYZACJI KIEROWANIA MASZYNAMI ROLNICZYMI

Streszczenie. W wyniku zwiększania się możliwości obliczeniowych komputerów w badaniach zachowania pojaz-

dów zaczęły pojawiać się ich złożone, nieliniowe modele. Jednak istotną ich wadą jest konieczność zebrania dużej liczby danych opisujących własności modelowanych pojazdów. Jest to szczególnie istotne, gdy model jest przeznaczony do wykorzystania na wstępnym etapie projektowania, gdy wielu danych jeszcze brak. Brakujące i niepewne dane zmniejszają dokładność wyników obliczeń symulacyjnych, co stawia w wielu przypadkach pod znakiem zapytania użyteczność takich modeli.

W prezentowanym artykule przedstawiamy propozycję wykorzystania prostych, liniowych modeli w systemach wspo-

magających pracę kierowcy maszyny rolniczej lub rolniczego zestawu transportowego. Poddano analizie dwa różne modele. Pierwszy to model strukturalny o dwóch stopniach swobody, a drugi model wykorzystuje funkcje transmitancji. Porównano rezultaty uzyskane za pomocą obliczeń symulacyjnych i za pomocą pomiarów. Przedstawiono koncepcję systemu wykorzystującego takie modele.

Słowa kluczowe: maszyny rolnicze, modelowanie, symulacja, wspomaganie kierowcy.

# Influence of moisture content on the mechanical properties and grinding energy requirements of dried quince (Cydonia Oblonga Miller)

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Summary. The objective of this study was to investigate the influence of moisture content on the mechanical properties and grinding energy requirements of dried quince fruits. The investigations were carried out on quince fruits (Cydonia oblonga Miller) - cv. Lescovac. The samples (mono layer) were dried at 55°C to adjust moisture water contents to: 10, 11 12, 13 and 14% w.b. The shear test was used for evaluation the mechanical properties of individual dried quince slices. The samples of dried quince were ground by using the laboratory hammer mill POLYMIX-Micro-Hammermill MFC equipped with round holes 3.0 mm screen. The results showed that an increase of quince moisture content form 10 to 14% caused the decrease of shear force and shear work from 62 to 48 N, and from 60 to 50 mJ, respectively. As the moisture increased the average particle size of ground material and specific grinding energy increased too from 0.52 to 0.60 mm and from 28.3 to 42.6 kJkg<sup>-1</sup>, respectively. The values of grinding efficiency index ranged from 0.31 to 0.18 m2kJ-1 and decreased as the quince moisture increased. The results showed that the quince moisture content, even in the narrow range (from 10 to 14%) has the strong influence both on quince mechanical properties and the grinding process.

Key words: quince, mechanical properties, grinding energy.

### **INTRODUCTION**

The quince (*Cydonia oblonga* Miller), is the sole member of the genus Cydonia and native to warmtemperate southwest Asia in the Caucasus region. It is a small, tree, growing usually for 3–5 m tall, related to apples and pears [Rejman 1994]. The quince tree shows high genetic variability. In Europe the existence of 30 different cultivars are verified, 19 in USA and around 86 in the old USSR, which were often mistaken by farmers. It stated that difficult classification is due to the amount of synonyms, polymorphism of fruits and leaves and the existence of many trees propagated by seeds [Rodríguez-Guisado et al. 2009]. Several studies have showed that quince tree is a good and low-cost natural source of phenolic acids and flavonoids [Oliveira et al. 2007, Costa et al. 2009]. These compounds could provide a chemical basis to some health benefits claimed for quince leaf and fruit in folk medicine, namely in cardiovascular diseases, haemorrhoids, bronchial asthma, and cough [Yildirim et al., 2001, Oliveira et al. 2008, Costa et al. 2009].

Quince is a golden yellow pome fruit, fleshy, downy, and with rich aroma and variable number of seeds. It shows different shapes, sizes and weights depending on cultivars [Rivera et al., 1997]. The mass of fruit ranged usually from 100 to 200 g [Wojdyło and Oszmiański 2010]. Quince fruit is not very appreciated for fresh market because of pulp hardness, bitterness and astringency. But when ripe, quince yields pleasant, lasting and powerful flavour. In the food industry quince fruits demanded for processing marmalades, jams, jelly and cakes production [Silva et al., 2002, 2005, Ferreira et al. 2004]. Quince fruits are very aromatics and can be used as flavouring. The 82 different compounds consist of quince fruit aroma [Umano and in 1986]. The industrially manufactured quince jam is prepared with quince puree, sugar and additives (preservatives such benzoic and sorbic acids, antioxidants such as ascorbic acid, acidity regulators such as citric and tartaric acids, etc) [Silva et al. 2006].

There are no work concerning the mechanical properties and grinding characteristics of dried quince fruits. Drying and grinding are two very important and energyconsuming processes in the food industry [Rudy 2009]. It is worth noting that the grinding methods of dried fruits are not enough developed. Dried and ground quince fruits can be used as flavouring with prohealth properties.

The objective of this study is to investigate the influence of moisture content on the grinding energy requirements of dried quince fruits. The mechanical properties of fruits were also evaluated.

### MATERIALS AND METHODS

The investigations were carried out on quince fruits (*Cydonia oblonga* Miller) - cv. Lescovac collected in 2011 at Lublin Voivodeship. The dry matter content was evaluated according to PN-ISO 1026:2000. Fat percentages were assessed by a Soxhlet extractor according to the Association of Official Analytical Chemists (AOAC, 1984) and the crude fiber ant the sugar contents were determined according to the method presented by Rodríguez-Guisado et al. [2009]. The fruits were cut on slices 3 mm thick and the round samples (10 mm diameter) were prepared by using a special blanking die. The samples (mono layer) were dried at 55°C to adjust moisture water contents to: 10, 11, 12, 13 and 14% w.b. ( $\pm$ 0,1%).

The shear test was used for evaluation the mechanical properties of individual dried quince slices. The singleblade knife (length 60 mm, high 35 mm, thickness 1,0 mm) was used for the test. During the test the knife displaced with the speed 10 mm·min<sup>-1</sup> along the special accessory with a gap. On the basis of obtained shear curves (Fig. 1) and by using special computer software the maximum shear force  $(F_{max})$  and shear work (W) were evaluated.

The samples of dried quince were ground by using the laboratory hammer mill POLYMIX-Micro-Hammermill MFC equipped with round holes 3.0 mm screen. The peripheral speed of the hammers was 17 ms<sup>-1</sup>. The changes occurring in the values of power consumption of the electric current during the grinding process were recorded with a frequency of 200 Hz by using the laboratory equipment, including the grinding machine, the power transducer, and a special data acquisition card, PCL818 L, connected to a computer. The grinding energy was calculated by using special computer software according to the methodology described by Laskowski et al. (2005). The ground material was collected for sieve analysis. Samples were sieved for 5 min on a Thyr 2 sifter, using 200-mm diameter wire mesh sieves of 1.6, 1.0, 0.63, 0.5, 0.4, 0.315 and 0.2 mm.



Fig. 1. An example of shear curve of dried quince

The average final particle size (d) was calculated as follows (Velu et al., 2006):

$$d = \sum_{i=1}^{n} \Phi_i d_i, \, \text{mm}$$
 (1)

where  $\Phi$  represents the differential weight fraction (kg kg<sup>-1</sup>) of particles passing through the aperture size  $d_i$  (mm).

The specific grinding energy  $(E_r)$  was determined as the ratio of the grinding energy to the mass of the material taken for grinding. The grinding efficiency index was calculated as a ratio of the grinding energy to the surface area of the pulverized material (Le Deschault de Monredon et al., 1999). The surface area of the pulverized material was evaluated according to the procedure described by Velu et al. (2006). The Sokołowski's grinding index was calculated on the basis of the size reduction theory described by Sokołowski (1996).

The measurements of grinding energy were replicated 10 times. The distribution of the particle size was evaluated thrice and the values of  $E_g$  and  $K_s$  were calculated from the average particle size ( $\dot{d}$ ). The obtained data was further subjected to the statistical analysis and the consequent evaluations were analyzed for a variance analysis. The statistical differences between the two treatment groups were estimated through Tukey's test. Statistical tests were evaluated by using the Statistica 6.0 software (StatSoft, Inc., Tulsa, USA). All the statistical tests were carried out at a significance level of  $\alpha = 0.05$ .

### **RESULTS AND DISCUSSION**

The average values of quince fat, fiber and sugar content were 1.68 ( $\pm$ 0.1), 1.8% ( $\pm$ 0.1), and 13.8 ( $\pm$ 1.3%), respectively. The results of quince mechanical properties showed that an increase of quince moisture content caused a decrease of shear force average from 62 to 48 N (Fig. 2). The strong linear relationship was found between the quince moisture content and this parameter (r = -0,991).



Fig. 2. The relation between quince moisture content and shear force; the values designated by the different letters are statistically significantly different ( $\alpha = 0.05$ )

The shear work of quince slices also decreased as the moisture increased (average form to 60 to 50 mJ) (Fig. 3). The relation between quince moisture content and the shear work was described by using the quadratic equation ( $R^2 = 0.987$ ).

The shear force is one of the most often used parameter to describe the mechanical properties of food, especially the food texture. The decrease of quince shear
force and shear work is caused by plastification effects of water on the material structure. This effect is demonstrated in many of others studies [Marzec and Lewicki 2005, Pittia and Sacchetti 2008].



Fig. 3. The relation between quince moisture content and shear work; the values designated by the different letters are statistically significantly different ( $\alpha = 0.05$ )



Fig. 4. Relation between the moisture content and the average particle size of ground quince; the values designated by the different letters are statistically significantly different ( $\alpha = 0.05$ )

The particle size distribution of the ground dried quince fruit are given in Table 1. The results showed that the increase of moisture content had the greatest influence on the mass fractions of middle (0.63-0.8 mm) and the fine (< 0.2 mm) particles. The fraction of particles 0.63-0.8 mm increased from 16.8 to 21.4%, whereas the mass fraction of fine particles decreased from 17.6 to 10.3%. The particle size distribution is very important

Table 1. Particle size distribution of dried quince

form the technological point of view, because it has an effect on many processes, and thus decides about the quality of the final products.

The increase of quince moisture content caused a slightly increase of average particle size from 0.52 to 0.60 mm. However the differences between the values of this parameter obtained for quince moisture content form 12 to 14% were not statistically different. The relation between the average particle size and the moisture content was described by using a quadratic equation ( $R^2 = 0.945$ ).



Fig. 4. Relation between the moisture content and the specific grinding energy of dried quince; the values designated by the different letters are statistically significantly different ( $\alpha = 0.05$ )

The changes of specific grinding energy were presented on Fig. 4. The results showed that as the kernel moisture increased the specific grinding energy also increased – average from 28.3 to 42.6 kJkg<sup>-1</sup>. The relation was described by using a quadratic equation ( $R^2 = 0.995$ ). There are many publications concerning the grinding energy requirements of food raw materials. However the most of them concerning the cereal grains [Dziki 2008, Rydzak and Andrejko 2011] and only a few are concerned a grinding characteristic of dried fruits or vegetables. Chakkaravarthi et al. [1993] studied the grinding process of dried carrot. They also found that as the carrot moisture content increased from 10 to 15%, the specific grinding energy increased too. The increase of moisture content causes an increase of material plastic-

Mass fraction (mm)	Moisture content (% w.b.)					
	10	11	12	13	14	
>1.6	0.1±0.01ª*	0.1±0.02ª	0.1±0.02ª	0.1±0.01ª	0.1±0.01ª	
1.0-1.6	7.5±0.2ª	8.3±0.2 <sup>b</sup>	9.1±0.1°	10.4±0.2 <sup>d</sup>	8.9±0.2°	
0.8-1.0	9.3±0.3ª	10.1±0.3 <sup>b</sup>	13.1±0.3°	12.5±0.3 <sup>d</sup>	13.0±0.3°	
0.63-0.8	16.8±0.3ª	18.4±0.4 <sup>b</sup>	21.7±0.4°	21.0±0.4°	21.4±0.5°	
0.4-0.63	24.7±0.5ª	24.8±0.5ª	25.0±0.4ª	27.3±0.5 <sup>b</sup>	27.6±0.3 <sup>b</sup>	
0.315-0.4	8.8±0.3ª	8.8±0.2ª	7.0±0.1 <sup>b</sup>	8.1±0.2°	8.6±0.2ª	
0.2-0.315	15.2±0.4ª	12.5±0.3 <sup>b</sup>	8.3±0.2°	10.0±0.3 <sup>d</sup>	10.0±0.1 <sup>d</sup>	
<0.2	17.6±0.4ª	17.0±0.3ª	15.7±0.3 <sup>b</sup>	10.4±0.2°	10.3±0.3°	

\*the values designated by the different letters in the line of table are statistically significantly different ( $\alpha = 0.05$ )

5.

ity and thus the material ground more difficult and the energy of plastic deformation is mainly converted to the heat and friction and thus the specific grinding energy increased. However the results of shear force and shear work indicated that increase of quince moisture content caused decrease of these parameters. Thus it is practical conclusion that during grinding of raw material about higher moisture content the size reduction should by given mainly by shear forces.

The results of grinding efficiency index were presented on figure 6. The strong linear relationship was found between quince moisture content and this index (r = -0,992). The grinding efficiency index ranged form 0.31 to 0.18 m<sup>2</sup>kJ<sup>-1</sup>. Similar values of this index were obtained for wheat grain by Dziki [2008].

The Sokołowski's grinding index changed from 32 to 55 kJkg<sup>-1</sup>mm<sup>0.5</sup>, as the quince moisture content increased. The relation between moisture content and this index was described by using the quadratic equation (Fig. 6).

All determined grinding indices confirmed that increase quince moisture content caused an increase of grinding energy requirements. However the highest changes of these indices were observed when quince moisture content ranged from 11 to 14%.



Fig. 5. Relation between the quince moisture content and the grinding efficiency index; the values designated by the different letters are statistically significantly different ( $\alpha = 0.05$ )



Fig. 6. Relation between the quince moisture content and the Sokołowski's grinding index, the values designated by the different letters are statistically significantly different ( $\alpha = 0.05$ )

#### CONCLUSIONS

- 1. The results showed that an increase of quince moisture content from 10 to 14% caused the decrease of shear force and shear work.
- 2. As the moisture increased the average particle size of ground material increased, too. The highest changes were observed in the mass fraction of middle (0.63-0.8 mm) and the fine (< 0.2 mm) particles.
- Both specific grinding energy and Sokołowski's grinding index increased as the quince moisture content increased, from 23.8 to 42.6 kJkg<sup>-1</sup> and from 32 to 55 kJkg<sup>-1</sup>mm<sup>0.5</sup>, respectively.
- The values of grinding efficiency index ranged from 0.31 to 0.18 m<sup>2</sup>kJ<sup>-1</sup> and decreased as the quince moisture increased.
- 5. The results showed that the quince moisture content, even in the narrow range (from 10 to 14%) has the strong influence both on quince mechanical properties and the grinding process.

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WPŁYW WILGOTNOŚCI NA WŁAŚCIWOŚCI MECHANICZNE I ENERGOCHŁONNOŚĆ ROZDRABNIANIA SUSZONEJ PIGWY (*CYDONIA OBLONGA* MILLER)

Streszczenie. Celem pracy było określenie wpływu wilgotności na właściwości mechaniczne i energochłonność rozdrabniania suszonej pigwy. Materiał badawczy stanowiły owoce pigwy (Cydonia oblonga Miller) - odmiany Lescovac. Próbki o średnicy 10 mm i grubości 3 mm suszono w pojedynczej warstwie w temperaturze 55°C do osiągnięcia różnych poziomów wilgotności: 10, 11 12, 13 i 14%. Dla tak uzyskanego materiału określono siłę cięcia i pracę ciecia pojedynczych próbek. Proces rozdrabniania przeprowadzono, wykorzystując laboratoryjny rozdrabniacz bijakowy POLYMIX-Micro-Hammermill MFC wyposażony w sito o średnicy otworów równej 3.0 mm. Na podstawie uzyskanych wyników badań stwierdzono, że wzrost wilgotności suszu w przedziale 10-14%pwodował spadek siły cięcia i pracy cięcia, odpowiednio od 62 N do 48 N i od 60 mJ do 50 mJ. Ponadto wzrost wilgotności próbek powodował spadek średniego wymiaru cząstki śruty (od 0.52 to 0.60 mm) oraz wzrost jednostkowej energii rozdrabniania od (28.3 do 42.6 kJkg<sup>-1</sup>) i wskaźnika efektywności rozdrabniania (od 0.31 do 0.18 m<sup>2</sup>kJ<sup>-1</sup>). Na podstawie uzyskanych wyników badań stwierdzono, że zmian wilgotność suszu pigwy, nawet w wąskim zakresie od 10 do 14% miał silny wpływ zarówno na właściwości mechaniczne, jak i na proces rozdrabniania.

Słowa kluczowe: pigwa, właściwości mechaniczne, energia rozdrabniania

# The size reduction theories of solid foods

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Summary. The paper presents the characteristics of grinding processes of solid foods. Especially the factors determining the size reduction process of solid foods were described and the most commonly used grinding theories were presented. The most important grinding laws were discussed. It can be concluded that the description of grinding process of solid foods is more complicated than of the comminuting process of other materials such as minerals and there are neither universal theories reported today nor any empirical comminution laws describing the process of solid foods size reduction over the entire range of particle sizes, especially in the field of ultrafine grinding.

Key words: grinding, food, grinding energy.

## INTRODUCTION

Size reduction has got many benefits in solid food processing. For example, dry milling yields flour and semolina, which can be used for making breakfast cereals, puffed snacks, pasta products and staple food items like cuscus. Dry milling has also been reported to help in redistribution of aflatoxins which got concentrated in the by-products during screening, whereas the main products contained only 12–30% of the level in the original grain [19]. This size reduction process is usually conducted by mechanical destruction of large fragments by impact or compressive action in devices of various engineering designs.

However, this process is one of the most energy consuming ones in food processing. For example, grinding consumes a majority of the total power during the wheat flour milling and during feed production. Among the physical properties of solid foods, the mechanical properties have the greatest influence on grinding energy. The amount of energy needed to fracture food is determined by its tendency to crack (its friability), which in turn depends on the structure of the food. Harder foods absorb higher energy and consequently require a greater energy input to create fractures [6]. The method of grinding depends on the properties of raw material. For example, compression forces are used to fracture friable foods; combined impact and shearing forces are necessary for fibrous materials, and shearing forces are used for fine grinding of softer foods. It is thought that foods fracture at lower stress levels if force is applied for longer times. The extent of size reduction, energy expended and the amount of heat generated in food, therefore, depend on both the size of the forces that are applied and the time in which the food is subjected to the forces [7].

Moisture content greatly affects the mechanical properties of foods. Figure 1 presents an example of compression curves obtained for barley kernels with different moisture contents. Thus, the water content significantly affects both the degree of fineness and the mechanism of breakdown in foods. Dry solid foods are brittle and easy to grind, they also need less energy for grinding [12]. An increase in water content causes an increase in food plasticity, especially when higher energy is required for grinding. During the comminution of solid foods, also the raw material temperature has a significant influence on the grinding results. Low temperature causes change of mechanical properties of food. The materials become brittle, they crumble easily, permitting grinding to a finer and more consistent size. An especially considerably smaller size can be obtained under cryogenic conditions [9]. Apart from this grinding in inert atmosphere of liquid nitrogen, gas reduces the risk of fire hazards and dust explosion [13].

Three types of force are used to reduce the size of foods: compression forces, impact forces and shearing (or attrition) forces. In most size reduction equipment all the three forces are present, but often one is more important than the others. For example, when hammer mill is used for pulverizing, the impact forces are more important than shearing forces, and compression forces are the least important [5].



Fig. 1. Examplary curves obtained during compression of barley kernel with different moisture contents, F – loading force, L – displacement of measuring head,  $F_r$  – rapture force

Grinding energy is one of the most common measurement parameter. To calculate the needed grinding energy against the grain size reduction many of size reduction theories were proposed. The aim of the work was to work out the characteristics and comparison of the grinding laws.

# THE GRINDING LAWS

The amount of energy required for size reduction of solid foods can be theoretically calculated based on the following equation:

$$\mathbf{d}E = -K\frac{\mathbf{d}x}{x^n},\tag{1}$$

where: dE is the energy required in breaking a unit mass of diameter x about size dx, K and n are constants depending on the ground material and grinding methods.

The relation (1) has been classically interpreted in many ways, referred to as Rittinger, Bond, Kick, Sokołowski and other grinding theories. The equation (1) has many solutions depending on n value. After the integration of equation (1) in the range from D to d we obtain:

$$E = \int_{D}^{a} -Kx^{-n} \mathrm{d}x, \qquad (2)$$

where: *D* and *d* represent the particle size before and after grinding, respectively. When we assume, that n > 1, the solution of equation (2) is the following:

$$E = \left(\frac{K}{n-1}\right) \left(\frac{1}{d^{n-1}} - \frac{1}{D^{n-1}}\right).$$
 (3)

When n = 1, integration of the basic equation gives Kick's law [11]:

$$E_{K} = K_{K} (\ln D - \ln d). \tag{4}$$

The Kick's law states that the energy required to reduce the size of particles is proportional to the ratio of the initial size of a typical dimension (for example the diameter of the particles) to the final size of that dimension. This relation is derived directly form the elasticity theory of ideal brittle solids. In practice it has been found that Kick's law gives reasonably good results for coarse grinding in which there is a relatively small increase in surface area per unit mass [8].

Rittinger based on empirical findings assumed that n = 2 and the integration of equation (2) give the following solution:

$$E_R = K_R \left(\frac{1}{d} - \frac{1}{D}\right). \tag{5}$$

Rittinger's law [5] states that the energy required for size reduction is proportional to the change in surface area of the particles. Rittinger's law gives better results with fine grinding where there is a much larger increase in surface area.

According to Rittinger [5], the D and d should be calculated as follows:

$$D = \frac{1}{\sum_{j} \frac{G_{j}}{D_{j}}},$$
(6)

$$d = \frac{1}{\sum_{i} \frac{g_i}{d_i}},\tag{7}$$

where:  $G_j$  and  $g_i$  represent the mass fractions of particles  $D_i$  and  $d_i$ , respectively.

Bond [2] assumed that n = 1.5 and the integration of equation (2) give the following solution:

$$E_{B} = K_{B} \left( \frac{1}{\sqrt{d_{80}}} - \frac{1}{\sqrt{D_{80}}} \right), \tag{8}$$

where:  $K_B$  is the Bond's constant and expresses the energy needed to reduce the unit of mass theoretically from infinity to such a size for which 80% of particles is sieved to values lower then 100 µm [15].

Bond expressed  $K_{B}$  as function of  $W_{i}$ :

$$E_{B} = 10W_{i} \left( \frac{1}{\sqrt{d_{80}}} - \frac{1}{\sqrt{D_{80}}} \right), \tag{9}$$

where:  $W_i$  is defined as work index and characterizes the resistance of material to grinding. This index can be also defined as comminution energy of the unit of mass from infinity size up to  $100 \ \mu m$  [4]:

$$E(\infty \to 100) = 10W_i(\frac{1}{100} - \frac{1}{\sqrt{\infty}}) = W_i.$$
 (10)

Using the laboratory methods, Bond determined, the values of  $W_i$  for different materials. Therefore, his grinding theory is very often used in practice. Bond's law combines the Kick's and Rittinger's laws by means of fitting factors which take into account the mechanical properties of the materials subjected to size reduction and their destruction conditions.

However, it is worth noting that the values of D and d in the equations (4) and (5) had different meanings in comparison to equation (9), although many authors have not differentiated between them [4, 20]. Sokołowski [17] has found out that the parameters D and d should be calculated as follows:

$$D_{w} = \left(\frac{1}{\sum_{j} \frac{G_{j}}{D_{j}^{w}}}\right)^{\frac{1}{w}}, \qquad (11)$$
$$d_{w} = \left(\frac{1}{\sum_{j} \frac{g_{j}}{d_{i}^{w}}}\right)^{\frac{1}{w}}, \qquad (12)$$

where:  $G_j$  and  $g_i$  have the same meaning as in the equations (6) and (7), respectively.

Sokołowski [17] showed that the value of exponent (*w*) changed from 0.25 to 0.85 for comminuted materials and when we assume the average value of w = 0.5, the error of estimation is low, but the solutions of equations (11) and (12) are simple, and we obtain:

$$D_{0,5} = \left(\frac{1}{\sum_{j} \frac{G_{j}}{\sqrt{D_{j}}}}\right)^{2},$$
(13)

$$d_{0,5} = \left| \frac{1}{\sum_{j} \frac{g_j}{\sqrt{d_i}}} \right| , \qquad (14)$$

then, the solution of equation (3) can be calculated as follows:

$$E_{S} = K_{S} \left( \frac{1}{\sqrt{d}_{0,5}} - \frac{1}{\sqrt{D}_{0,5}} \right), \tag{15}$$

where:  $K_s$  is the Sokołowski's constant and  $d_{0.5}$  and  $D_{0.5}$  represents the particle size before and after grinding, respectively

It is worth noting that equations (4), (5), (8) and (15) were developed mainly from studies of hard mineral materials such as coal and limestone, but many authors have used these laws for description of comminution process of solid foods. Djantou et al. [4] studied the effect of pre-treatment on the grinding ability of dried mango for powder production. They observed that values of constants  $K_{\kappa}$  and  $K_{R}$  differed significantly. Walde et al. [20] studied the grinding characteristics of microwave dried wheat. They found that the values of  $K_{\kappa}$ . Pujol et al [16] showed that Sokołowski's constant changed from 22 kJkg<sup>-1</sup>mm<sup>0.5</sup> for soft wheat to 54 kJkg<sup>-1</sup>mm<sup>0.5</sup> for *durum* wheat. Dziki [5] found that this constant also depended on the method of grinding.

Charels [3] extended existing theories of comminution and proposed the equation to calculate the comminution energy (*E*) necessary to obtain the particle size *y* from the material with the initial size  $x_{max}$ :

$$E = \int_{0}^{y} \int_{x_{\max}}^{x} (-Kx^{-n} dx) dM, \qquad (16)$$

where: dM represents the mass of particles in the range of sizes from *x* to *x*+d*x*. According to Stambolidis [18] the mass of particles with sizes lower then *x* can be expressed as:

$$M_x = W_o \left(\frac{x}{y}\right)^{\alpha},\tag{17}$$

where:  $W_o$  is the mass of particles taken for comminution and  $\alpha$  is the coefficient of particle size distribution. The derivative of equation (17) is as follows:

$$\mathrm{d}M_x = \alpha W_0 \frac{x^{\alpha - 1}}{y^{\alpha}} \mathrm{d}x \,. \tag{18}$$

The solution of equation (16), after dividing at both sides of equation by  $W_o$  can be expressed as:

$$E_{Ch} = \frac{K_{Ch}\alpha}{(n-1)(\alpha - n + 1)} y^{1-n},$$
 (19)

where:  $K_{Ch}$  is a constant dependent on the properties of ground material.

The detailed way of determining equation (19) and coefficients  $\alpha$  i *n* was described by Stamboliadis [18]. He found out that for most materials the expression  $(\alpha - n + 1)$  is equal to zero, thus the equation (19) cannot be used to determine the energy of comminution and he proposed the formula:

$$E_s = \frac{C}{n-1} \frac{\ln y^{\alpha}}{y^{\alpha}}.$$
 (20)

Hukki [10] assumed that in the equation (19) exponent (1-n) is not constant, but depends on the size of comminuted material and degree of fineness. For large particles (order of magnitude 0,01 m) and when the degree of fineness is low, the grinding energy is mainly derived from the volume of material and Kick's theory of grinding is adequate. For smaller grinding (order of magnitude of ground particles 0,01 m) the Bond's grinding theory should be used and for the finest grinding (orders of magnitude 0,001), the grinding energy is proportional to the area of comminuted particles and thus the Rittinger's grinding theory can be used. It is caused by the fact that the small particles need much more stresses to comminution [1]. Similar conclusions were obtained by Morrell [14] which modified the Bond's theory and proposed the following equation:

$$E_r = M_i \cdot K(d_{80}^{f(d)} - D_{80}^{f(D)}), \tag{21}$$

where: *Mi* represents the index depending on the method of grinding, *K* is the grinding constant, and  $d_{80}$  and  $D_{80}$  have the same meaning as in the equation (8). For particles with size *x*, the function describing the changing of exponent can be calculated as follows [14]:

$$f(x) = -(a + x^b),$$
 (23)

where: a and b are constants, and x is such a size of the screen diameter for which 80% of particles are sieved.

Beside the described grinding theories there are many others, but they are seldom used in practice.

# CONCLUSIONS

- The description of grinding of solid foods is more complicated than of the comminuting processes of minerals or metals. It is due to the fact that the results of grinding depend strongly on food moisture content and temperature.
- Some foods are sensitive to increases in temperature or oxidation during comminution, and mills are therefore cooled by chilled water, liquid nitrogen or carbon dioxide.
- 3. There are neither theories reported today nor any empirical comminution laws describing the process of solid foods comminution in the field of fine and ultrafine grinding.
- 4. None of the common mathematic approximations of the grinding behavior of solid foods is equally accurate over the entire range of particle size.

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# TEORIE ROZDRABNIANIA ŻYWNOŚCI O POSTACI STALEJ

S tr e s z c z e n i e. W pracy przedstawiono charakterystykę procesu rozdrabniania żywności o postaci stałej. W szczególności omówiono czynniki determinujące proces rozdrabniania żywności oraz skupiono się na najistotniejszych teoriach procesu rozdrabniania. Wykazano, że opis procesu rozdrabniania żywności jest znacznie bardziej skomplikowany niże dekohezja innych materiałów, takich jak np. materiały mineralne i nie ma uniwersalnej teorii rozdrabniania opisującej proces redukcji wymiarów żywności w całym przedziale wielkości cząstek, a w szczególności podczas rozdrabniania bardzo drobnego.

Słowa kluczowe: rozdrabnianie, żywność, energia rozdrabniania.

# Thermal and physical properties of some refractory layers used in lost foam technology

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S u m m a r y. Evaluation of the applicability of the selected coatings applied in foundry practice was determined on the basis of comparative measurements of the thermal and physical and mechanical properties. Thermal and physical properties: specific heat, thermal expansion, density, thermal diffusivity and thermal conductivity were established for the three refractory layers utilized in lost foam casting technology. The obtained results can be utilized in optimization of modified refractory layers spread on the foamed patterns. More durable and more resistant to high temperature material # 1 has a worse heat transfer parameters than the coatings # 2 and # 3, which may be indicative of its higher permeability.

Key words: lost foam casting, evaporative pattern, refractory (ceramic) layer, thermal conductivity, thermal diffusivity, specific heat.

# INTRODUCTION

Lost foam technology is a kind of casting process using patterns made of foamed polystyrene, which can evaporate when the molten metal is poured into the mould. Each pattern is combined into a single set, together with a gating system using gluing. A pattern set prepared in such a way is coated with a ceramic layer. Complex patterns are molded and the mould is compressed by vibration. When pouring, liquid metal acts on the model, causing it to evaporate (Fig.1). Foaming is performed not only to make the model of the required shape, but also to achieve the required density of the model. One of the main parameters determining the proper course of evaporation process during the filling of the mold with liquid metal, are physical and chemical properties of the ceramic coating applied to a polystyrene pattern. These factors include permeability, mechanical strength and thermal and physical properties of ceramic coatings. Ceramic coatings that are applied to polystyrene pattern should have defined physical and chemical properties, including resistance to thermal and erosive effect of liquid

metal and the suitable permeability of gases produced from gasified polystyrene model.



Fig. 1. Lost foam process [1]

The values of basic parameters of the refractory (ceramic) layer covering the polystyrene pattern, such as density, specific heat, thermal conductivity, etc. have a significant impact on the process of pattern's gasification and indirectly affect the flow and filling the mould by the liquid metal.

The other parameters characterizing the heat exchange processes in the system metal-mould (Fig. 1) are permeability of refractory layer and heat transfer parameter (Heat Transfer Coefficient, HTC).

These parameters represent the basic thermal characteristics used in computer simulation methods, currently heavily developed. For example, they are used to simulate the solidification processes with aim to minimize the porosity in aluminium alloys cast by lost foam technology [4]. A small number of literature sources devoted to research and analysis and a limited resource of thermal and physical databases provide incentives for comprehensive studies of thermal and physical properties of materials used in the lost foam method. The aim of the study was to determine the temperature dependence of thermal and physical parameters of the ceramic layer applied to a model of polystyrene in the perspective of the use of computer simulation data to the solidification and cooling processes of alloys cast by lost foam technology.

## MATERIALS AND EXPERIMENTAL PROCEDURE

Three ceramic layers consisting of grain matrix, binder and additives modifying and stabilizing the substance has been selected for the study of thermal conductivity. The properties of coatings are usually defined by means of their heat transfer characteristics (insulation properties, high conductivity, etc.) and the gas flow characteristics (low, medium or high permeability). With the increase of temperature requirements for ceramic coatings are getting higher. The study conducted at the Foundry Research Institute [...] has shown that with the increase of temperature of molten metal above 1400 °C the impact resistivity of coatings for thermal and hydrostatic effect of molten metal stream decreases.

Components required to prepare the liquid ceramic coating used for covering of polystyrene models are:

- solvent-water,
- adhesive-silica colloid,
- combination of polytetrafluoroethylene and stearinbutadiene latexes,
- a mixture of surface-active anionic and non-ionic,
- measure counteracting setting up a foam,
- refractory material meal.

Zirconcar is a mixture of mineral substance, containing zirconium and binders consisting of silica sol and the set of surfactants and organic latex.

#### **EXPERIMENTAL**

The complex, thermal and physical properties determination of refractory layers spread on patterns utilized in lost foam casting technology was performed, using modern thermal analysis equipment utilized in Foundry Research Institute.

Thermal conductivity (T) can be calculated according to the formula:

$$\lambda(T) = a(T)c_p(T) \ \rho(T) \tag{1}$$

where: a(T),  $c_p(T)$  and (T) denote thermal diffusivity, specific heat and density, respectively.

Thermal diffusivity was measured by means of laserflash Netzsch LFA 427/4/G apparatus shown in Fig. 2. This equipment and measurement technique enable determination of thermal diffusivity of metals, alloys and ceramic materials in the temperature range of RT  $\div$  1500°C with uncertainty of 3%.

Basing on thermal diffusivity data it is possible to calculate the thermal conductivity with 5% error in a whole temperature range. The equipment consists of high temperature furnace, sample holder, high power 1064 nm Nd:YAG laser, infrared InSb detector with LN2 cooling.

The principle of measurement of thermal diffusivity by means of laser-flash method is heating of the frontal sample's surface with a very short laser impulse resulting in temperature increase on the opposite side. This signal is measured in a function of time, by means of infrared detector. Data acquisition unit enables signal analysis with pulse length correction and heat loss corrections utilized non-linear regression for Cowan fit and improved Cape-Lehman model characterized by multi-dimensional heat loss and non-linear regression.

DSC measurements are used for identification and analysis of phase transformations proceeding during heating or cooling, determination of the enthalpy changes in solid and liquid states and for determination of specific heat in fuction of temperature.

Differential scanning calorimeter Netzsch DSC 404C Pegasus was utilized for determination of specific heat of material under investigation. according to the comparative, ASTME 1269 standard method.

Fig. 3. shows the principle of determining of specific heat by comparative method consisting of three DSC measurements (curves): empty crucible, crucible + standard (sapphire) and crucible + sample.

In this case specific heat can be calculated from proportion:

$$c_{sample} = c_{standard} (m_{standard} / m_{sample}) (D_{sample} / D_{standard})$$
(2)

The measurements were performed using platinum crucibles with alumina liners and sapphire as standard sample, with heating rate 20 K/min with atmosphere of pure argon. The specific heat values were calculated using DSC analysis software with measurement uncertainty of  $\pm 2.5\%$  in the whole temperature range.



Fig. 2. The principle of specific heat measurement with sapphire as standard

According to density definition  $\rho(T) = m/V(T)$  the knowledge of volume changes on temperature V(T) is required and the dilatometric method, which enables determination of  $\Delta L/L$  is adequate.

Simple calculations lead to the formula:

$$\rho = \rho_{o} / (1 + \beta_{m} \Delta T)^{3} = \rho_{o} / (1 + \Delta L / L_{o})^{3}$$
(3)



Fig. 3. Exemplary analysis software screenshot showing dependence of thermal diffusivity on temperature for coating# 1.

 $Density \rho_o = m/V_o a troom temperature can be determined by means of hydrostatic balance or pycnometric method.$ 

Dependence of density on temperature was found using dilatometric method and Netzsch DIL 402C/4/G was applied.

The measurements were performed in pure argon atmosphere, at temperature RT, 200, 400, 600, 800, 1000 and 1200 °C using three laser shots at every temperature step.

#### RESULTS

Exemplary chart of analysis software (Fig.3) shows the dependence of averaging thermal diffusivity on temperature for coating #1. The shape of laser shot (impulse) lasting 0.8 ms was shown in lower left edge of the figure and the laser shot response recorded by means of IR detector has been shown in lower right end of the figure.



Legend: pokrycie - coating

Fig. 4. Specific heat of investigated coatings



Legend: pokrycie - coating

Fig. 5. Relative linear expansion of investigated coatings



Legend: pokrycie - coating

Fig. 6. Temperature dependence of refractory layers under investigation

The evaluated values of thermal diffusivity and thermal conductivity are given in Table 1.

Tab.	1.	Thermal	diffusivity	( <i>a</i> ) a	nd th	ermal	conduct	ivity
( <b>b</b> ) of i	nve	estigated	coatings					

Sample	T, ℃	a, mm²/s	$\lambda$ , W/mK
coating #1	50,3	$0,373 \pm 0,005$	0,461
	200,2	$0,280 \pm 0,003$	0,435
	400,2	$0,\!175 \pm 0,\!001$	0,294
	600,3	$0,163 \pm 0,001$	0,262
	800,4	$0,\!170 \pm 0,\!009$	0,26
	1000,5	0,186 ± 0,013	0,267
	1200,2	$0,287 \pm 0,034$	0,482

coating #2	50,2	$0,385 \pm 0,002$	0,436
	200,1	$0,321 \pm 0,002$	0,468
	400,3	$0,206 \pm 0,005$	0,34
	600,3	$0,\!185 \pm 0,\!001$	0,259
	800,4	$0,193 \pm 0,006$	0,233
	1000,2	$0,259 \pm 0,025$	0,266
	1200,2	$0,359 \pm 0,023$	0,617
coating #3	50,3	$0,368 \pm 0,007$	0,45
	200,1	$0,309 \pm 0,001$	0,46
	400,3	$0,207 \pm 0,003$	0,342
	600,3	$0,\!188\pm0,\!001$	0,282
	800,4	$0,\!191 \pm 0,\!005$	0,277
	1000,2	$0,266 \pm 0,009$	0,376
	1200,2	$0,380 \pm 0,045$	0,823

The measured and calculated results are summarized and compared in Fig.7a,b.



**Fig. 7.** The summary of investigations – thermal diffusivity (a) and thermal conductivity (b)

Dilatometric studies show that the coating # 1 is characterized by the highest thermal expansion and the lowest density. The destruction of this coating indicated by shrinkage of dilatometric curve, begins at ca 940 °C i.e. occurs about 100 °C higher than for coatings # 2 and # 3. This proves the durability and resistance to high temperature coating # 1. It may be due to the absence in this material unidentified phase transition at around 480 and 680 °C, which can be seen to the coatings # 2 and # 3. Observation of thermo-physical data connected with the heat conduction shows that the coating # 1 has the lowest temperature conductivity in the whole temperature range. The obtained results suggest that the more durable and more heatresistant material # 1 has a worse ability to heat removing and greater permeability than the coatings # 2 and #3.

## CONCLUSIONS

1. Thermal and physical properties: specific heat, thermal expansion, density, thermal diffusivity and thermal conductivity were established for the three refractory layers utilized in lost foam casting technology.

- 2. The obtained result will be the enriched thermal and physical properties database utilized in computer simulation of casting processes performed in evaporative pattern foundry applications.
- 3. The obtained results will be utilized in optimization of modified refractory layers spread on the foamed patterns.
- 4. More durable and more resistant to high temperature material # 1 has a worse heat transfer parameters than the coatings # 2 and # 3, which may be indicative of its higher permeability.

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# BADANIE PRZEWODNOŚCI CIEPLNEJ WYBRANYCH WARSTW CERAMICZNYCH STOSOWANYCH W TECHNOLOGII MODELI ZGAZOWYWANYCH

S treszczenie. Warstwa pokrywająca model polistyrenowy musi być zdefiniowania poprzez wyznaczenie podstawowych parametrów termofizycznych (gęstość, ciepło właściwe, przewodność cieplna itp.). Należy również określić jej przepuszczalność gdyż ona decydować będzie o przebiegu procesu zgazowywania modelu a pośrednio na przepływ (lub jego brak) metalu w formie. Ponieważ przez warstwę pokrywającą model następuje wymiana ciepła ciekłego metalu z luźno wsypanym piaskiem formy musi być również zdefiniowane współczynniki pojemności i przewodności cieplnej warstwy ceramicznej. W artykule omówiono sposób pomiaru o raz uzyskane wyniki.

Słowa kluczowe: technologia modeli zgazowywanych, modele zgazowywane, pokrycia ceramiczne, przewodność i pojemność cieplna warstwy ceramicznej.

# Poisson's ratio of anisotropic biological media

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Summary. A model of a honeycomb structure is presented showing that in particular conditions Poisson's ratio determined for bodies revealing such structure may well exceed not only 0.5 limit but even may reach values above 1. The model is based on a real cell structure observed in scanning electron microscopy images. Experimental results obtained for fresh tomato skin using a uniaxial strength test are presented and interpreted as an exemplary case. A model of a honeycomb cell is used to compare experimental and calculated results.

Key words: Poisson's ratio, tomato skin, mechanical properties.

#### INTRODUCTION

Studies performed on biological materials often lead to mechanical parameters that are beyond the limits of the elasticity theory. Particularly, Poisson's ratio (v) measured basing on uniaxial strength tests reaches values that exceed 0.5 or even 1.0. Poisson's ratio is a negative ratio of transverse dimension change to longitudinal dimension change of a body under a stress applied along the longitudinal direction [1, 12]. According to the elasticity theory [12, 18] for isotropic 3D media -1 < v < 0.5 and this limit is enhanced for 2D isotropic samples where -1 < v < 1. However, biological objects are rarely isotropic. Most of these materials have quite complicated structure and reveal different properties depending on geometrical directions chosen as the main axis in the uniaxial strength test. It is therefore necessary to stress that for such anisotropic 3D and particularly 2D materials the limits mentioned above become non valid. There are many examples in the literature showing, that Poisson's ratio reaches values "beyond the limits" [2, 13, 14, 17]. Among others Tilleman et al. [16] found that for studied biological materials Poisson's ratio ranged from 0.25 up to 0.85. Hamza et al. [10] measured Poisson's ratio for maize roots (whole roots, stele with cortex combined) and

obtained v=0.63. Elliott et al. [3] studied human patellar articular cartilage and found that Poisson's ratio in the surface zone is about 1.9 and in the middle zone about 0.6. Hepworth and Bruce [11] reported Poisson's ratio of the onion epidermal tissue that reaches 2.0.

In this work, a model of a honeycomb structure is presented showing that in particular conditions Poisson's ratio determined for bodies revealing such structure may well exceed not only 0.5 limit but even may reach values above 1. A honeycomb model can also be used to explain negative Poisson's ratio values. In that case so called re-entrant honeycomb structure is proposed [15]. As an exemplary case, experimental results obtained for fresh tomato skin are presented.

# EXPERIMENT

Poisson's ratio of the tomato skin was determined on the base of uniaxial strength tests. The method of random marking was used [5-8]. This method is based on the analysis of the image and the distance of mutual position of the points on the surface of the studied sample being under the tests of uniaxial stretching. After starting the test, the image of the stretched specimen together with graphite markers randomly sprayed on its surface and the current value of the tensile force corresponding to each image are transmitted to a computer memory. The signal from the tensometer is transmitted with the use of an analogue-to-digital converter to the computer memory and the registered image of the stretched specimen to the input of a video card. With the use of a CCD camera equipped with microscope lens which enabled to view the specimen at 240x320 pixel resolution and 5x magnification, it is possible to observe stretched specimen. The specimen is placed in clamping grips connected to a Megaton Electronic AG&Co. KT-1400 tensometer with a force measurement range of 0-100 N.

The main advantage of the used random marking method is that the obtained results are independent from the effects occurring at the edge areas of the specimen. It is also possible to perform measurements in the chosen place of the studied material. An additional advantage is a possibility of monitoring the force instead of the total increase of the strain as takes place in majority of strength testing machines.

## MODEL

The simplest model of the body that leads to Poisson's ratio exceeding 1.0 can be elaborated assuming the rhombic structure of tested specimen cells. Figure 1 shows a schematic view of changes occurring in such model structure under applied uniaxial force and defines characteristic geometric parameters of the rhombic cell. Assuming that the rhomb sides are perfectly stiff and only angles between them change, Poisson's ratio can be defined as:

$$v = -\frac{dy}{dx}.$$
 (1)

This simplification is possible because at the initial stage x=y. Taking into account that:

$$a^2 = x^2 + y^2,$$
 (2)

$$x = \frac{a\sqrt{2}}{2} + dx,$$
(3)

$$y = \frac{a\sqrt{2}}{2} + dy,$$
(4)

we obtain:

$$v = -\frac{dy}{dx} = -\frac{-\frac{a\sqrt{2}}{2} + \sqrt{a^2 - \left(\frac{a\sqrt{2}}{2} + dx\right)^2}}{dx}.$$
 (5)



**Fig. 1.** Hypothetical changes of a rhombic cell under an applied uniaxial force F. Parameters *a*, *x* and *y* determine a rhombic cell dimensions

Figure 2 shows For such structure Poisson's ratio reaches values above 1.0. This simple model has been applied earlier to explain results (v > 1) obtained for dried bean covers [4, 6] as their cell structure is similar to this assumed in the model. In the case of dried bean covers that are characterized by relatively stiff cell sides in comparison to a medium inside a cell, this model seems to be adequate. However, in the case of a fresh tomato skin a cross section images reveal rather a honeycomb structure of a cell than a rhombic one. Moreover sides of such honeycomb cells are surely not so stiff, so a more developed model should be used. The model should also



Fig. 2. Dependence of Poisson's ratio on a relative longitudinal dimension change

provide a constant value of Poisson's ratio when a longitudinal dimension of the cell changes.

Figure 3 presents a cross section image obtained for a fresh tomato skin (of fruits cv. Admiro) with the use of the BS300 TESLA scanning electron microscope (STM) at accelerating voltage of 15 kV [9]. The image illustrates the cell structure of a specimen. Therefore, in the model a corresponding structure has been assumed. Figure 4 shows a schematic view of the elongated honeycomb cells and also defines characteristic geometric parameters of the cell.

Momentary values of x, y and b under longitudinal strength are as follows:

$$x = x_0 + dx,\tag{6}$$

$$y = y_0 + dy, \tag{7}$$

$$b = b_0 + db, \tag{8}$$

where:  $x_0, y_0$  and  $b_0$  indicate cell dimensions at the initial stage.



**Fig. 3.** STM cross section image obtained for a fresh tomato skin (fruits cv. Admiro) [9]



Fig. 4. Schematic view of the elongated honeycomb cells used in the model. Parameters x, y and b determine a honeycomb cell dimensions

where:  $\varepsilon_y$  and  $\varepsilon_x$  are transverse dimension change and longitudinal dimension change of a body, respectively, and taking into account that

$$\varepsilon_x = \frac{dx + db}{x_0 + b_0},\tag{9}$$

$$\varepsilon_{y} = \frac{dy}{y_{0}},\tag{10}$$

we can calculate the transverse dimension change:

$$y = -\frac{v \cdot y_0 \cdot c \cdot dx}{x_0 + b_0},\tag{11}$$

where:

$$c = 1 + \frac{b_0}{x_0}.$$
 (12)

This provides that in the frame of the presented model Poisson's ratio remains constant during the honeycomb cell evolution. It is necessary to mention that from mathematical point of view there is no limitation of Poisson's ratio in the model.

## **RESULTS AND DISCUSSION**

Figure 5 presents as an example the experimental dependences  $\varepsilon_x(\sigma)$  and  $\varepsilon_y(\sigma)$ , where  $\sigma$  means stress, obtained for the stretched fresh tomato skin specimen. From the linear fits given in the insets the calculated Poisson's ratio v=0.825. Introducing this value into the model it is possible to estimate changes of longitudinal and transverse dimensions of the honeycomb cells. Figure 6 shows the calculated dependences  $\varepsilon_x$  and  $\varepsilon_y$  on a relative longitudinal dimension change

$$S = -\frac{2y_0vc^2}{x_0 + b_0} (dx)^2 + 2y_0c(1 - v)dx + 2y_0(x_0 + b_0).$$
(13)

dx/x. The input parameters  $x_0=100 \text{ }\mu\text{m}$ ,  $y_0=100 \text{ }\mu\text{m}$  and  $b_0 = 400 \ \mu m$  has been set basing on the image shown in Fig. 3. The assumptions taken in both presented models cause that the cross section surface S changes during a cell evolution (see Fig. 7). From this plot we note that the total surface of a cell cross section increases when dx/x < 0.105, reaches its maximum (at this point  $\Delta S/S =$ +0.1%) and for dx/x > 0.105 decreases, because the total cell surface follows equation (13) as calculated for honeycomb cell. It is also worth to note that the dependence of Poisson's ratio on a relative longitudinal dimension shown in Fig. 2 is nearly identical with that obtained by Hepworth and Bruce [11] who studied changes of Poisson's ratio of the onion epidermal tissue as a function of the tensile strain applied parallel to the long axis of the cell. Both experimental and the proposed by the authors unrestricted reorientation model results show that



Fig. 5. Experimental dependences  $\varepsilon_x(\sigma)$  and  $\varepsilon_y(\sigma)$  obtained for the stretched fresh tomato skin specimen



**Fig. 6.** Calculated dependences  $\varepsilon_x$  and  $\varepsilon_y$  on a relative longitudinal dimension change dx/x calculated for a honeycomb cell where  $x_0=100 \ \mu\text{m}$ ,  $y_0=100 \ \mu\text{m}$  and  $b_0=400 \ \mu\text{m}$ 



Fig. 7. Evolution of the cross section surface S of a honeycomb cell with the longitudinal dimension change dx

Poisson's ratio measured for biological media may well exceed 1.0 (in the case of results presented in the mentioned work, v reaches 2.0). The model presented here is based on another cell structure, however also proves that for biological anisotropic media, relatively high values of Poisson's ratio can be explained with models that are created basing on realistic cell structure, for example mimicking observed cross section images obtained with the use of the scanning electron microscopy.

## CONCLUSIONS

- 1. Poisson's ratio exceeding 1.0, frequently measured in biological materials, should not be considered as beyond the limits and therefore – not correct. The -1 < v < 0.5 limit for 3D materials and -1 < v < 1 for 2D materials is valid for isotropic body. Biological media are often anisotropic and therefore do not follow limits given by the elastic theory.
- 2. Models based on a real cell structure observed via different microscopy techniques, can be used to interpret high values of Poisson's ratio.
- 3. Model of a honeycomb cell seems to be adequate for interpreting results of mechanical parameters obtained from uniaxial strength tests of a tomato skin.

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#### WSPÓŁCZYNNIK POISSONA ANIZOTROPOWYCH MATERIAŁÓW BIOLOGICZNYCH

Streszczenie. W pracy zaproponowano model oparty na strukturze plastra miodu, umożliwiający wykazanie, że w szczególnych warunkach materiały o takiej strukturze mogą charakteryzować się współczynnikiem Poissona nie tylko przekraczającym wartość 0,5, ale nawet większym od 1. Model oparty jest na obrazach rzeczywistej struktury skórki pomidora obserwowanej przy użyciu skaningowej mikroskopii elektronowej. Wyniki doświadczalne uzyskane w testach jednoosiowego rozciągania skórek świeżego pomidora zostały poddane analizie, jako przykładowe. Model struktury plastra miodu został wykorzystany do porównania wyników doświadczalnych i obliczonych.

Słowa kluczowe: współczynnik Poissona, skórka pomidora, właściwości mechaniczne.

# The anisotropic nature of the strain of biodegradable film produced from TPS starch

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S u m m a r y. The paper presents results of research aimed at checking the anisotropic nature of the biodegradable film produced from potato starch. On the basis of tension test, Young's modulus as well as breaking force values were determined for material samples cut from the film in directions parallel and perpendicular towards to its production direction. Occurring differences in the longitudinal modulus of elasticity and breaking force values depended on the procedure of sample preparation and indicated the tested material anisotropic nature. Additionally, the influence of granulated raw material composition on the film thickness and strength parameters was examined.

Key words: biodegradable film, anisotropy, Young's modulus, breaking force.

#### INTRODUCTION

Growing demand for disposable packaging contributed to the significant development of the packaging market. Simultaneously it created a problem with the waste management. The major setback is presented by the synthetic packaging which vast amounts pollute the environment. One of the solutions to this problem is recycling. However, recycling generates high costs and brings difficulties with an appropriate waste segregation. Unquestionable merit of the biodegradable packaging is that it does not spoil the environment and constitute a serious alternative for plastics which composting and degradation requires large amounts of energy.

Regarding ecology, the most favourable way to reduce the used packages is to produce biodegradable package materials [2, 8]. The first stage of the biodegradation process concerning traditional synthetic polymers can concentrate on plastics modification or introduction of supplements capable of solar radiation absorption [11]. In recent years in the industry, materials obtained from polyolefine polymers supplemented with modified starch, also called thermoplastic starch (TPS), have been introduced. They belong to a generation of biodegradable materials based on natural resources. Starch is relatively cheap and fully biodegradable. It can get plasticized through the barothermal treatment as long as proper plasticizers are added [12, 15]. Unfortunately, the materials manufactured from a starch alone tend to brittle, are not water-resistant and change mechanical properties due to the recrystallization process. Determined strength parameters values also vary according to the way of load [5, 10, 17, 18]. In the case of biological samples, encountered difficulties stem primarily from the specific cellular and structural material building. The literature data shows that the plant material can exhibit both isotropic [6, 7, 13], as well as anisotropic [16, 18] character.

The aim of this study was to examine mechanical anisotropy through



**Fig. 1.** Stand for film extrusion [14]. The line was produced by SAVO, Wiązowna the Young's modulus and breaking force values determination for the biodegradable film produced from potato starch.

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#### MATERIALS AND METHODS

The thermoplastic starch granulate (TPS) was obtained by the extrusion cooking process, commonly known in the farm and food processing. The basic materials were potato starch "Superior" from ZPZ Łomża, technical glycerol purchased at ZPCH Chemical Plants Odczynniki Chemiczne in Lublin, water and emulsifiers: BRIJ 35 and TWIN 20 (alcohol derivatives). Table 1 presents the composition of the mixtures used in the research [14].

The process of film extrusion with the blow moulding method application was conducted in the Department of Food Processing Engineering on a specially designed production line for laboratory film (Fig.1).

The mechanical properties of obtained materials were studied using an original method of random markers [4]. The material for examination was thin-layer sheets of biodegradable film. Young's modulus and breaking force determination was carried out by subjecting the film samples to uniaxial tension test. Figure 2 shows the outline of the measuring system. It should to be mentioned that such a test usually requires calculation of the stress occurring near the clamps holding the sample while the main advantage of random markers test is the independence of the results from the boundary effects. The main assumption of the Saint - Venant principle, on which mentioned method is based is the fact that in a sufficiently large distance between the ends of the sample and mounting place, the stress distribution is homogeneous throughout its volume [1, 9].

The computer program "Videoo" [3] controlled process of collecting the data and the necessary calculations during the measurement.

Two types of samples were cut from the sheet of the film in order to carry the tests in both: the longitudinal and perpendicular axis of the sample regard to the direction of film production. The samples were dumbbell shape with a length of 40 mm and a width equal to 5 mm at its tapered part. Samples were cut



Fig. 2. A diagram of measuring station. C – camera, M – microscope object lens,  $S_1$  i  $S_2$  – clamps, T – tensometer, F – force

with a special blanking tool that provides dimensional stability. Since the method of random markers requires a third dimension, the thickness of the sample was measured with the micrometer (accuracy  $\pm$  0.01 mm) application. Each measurement series consisted of 15 repetitions. The value of Young's modulus *E* for each sample was determined from the tangent of the curve, describing the dependence of  $\varepsilon_x = f(\sigma)$ , slop angle, where  $\varepsilon_x$  - relative elongation in the direction of the x-axis (stretching direction),  $\sigma$  - stress value (MPa). The arithmetic mean of all 15 individual measurements was the total value of elasticity modulus *E*. The study also allowed determining the breaking force value as the maximum value of the force at which destruction of the sample occurred.

#### **RESULTS AND DISSCUSION**

Figure 3 presents the mean values of Young's modulus for the examined film, determined with the random markers method application. The values of longitudinal modulus of elasticity E differed depending on the choice of direction during sample preparation, which indicates the anisotropic nature of the tested material. In the case of samples that were cut parallel to the direction of film production, the value of Young's modulus was higher than calculated for the perpendicular direction. The highest values of E, above 200 MPa, were obtained for films I and II (Fig. 3a) and were almost two times higher than for samples that were cut in the perpendicular direction (Fig. 3b). Lower values of Young's modulus with increasing water content in the granules were noted for both ways of cutting the samples. Doubling the water content in the granules from 5 % to 10 % caused the decrease in Evalue by more than 15 % for samples cut in the direction of film production and more than 45 % for samples cut perpendicular. Samples of film III with 10 % of water content cut parallel to the direction of production were characterized by Young's modulus value at a level of 181 MPa, while for samples prepared in a perpendicular direction was nearly three times lower and amounted to 62.3 MPa (Fig. 3a and 3b).



a)



**Fig. 3.** Young's modulus average values with standard deviation for samples I, II III (Tab. 1) cut a) parallel and b) perpendicular to the direction of film production

Table 1. Biodegradable granulates material composition

Sample		Glicerol	Emulsifier	Water
Ι	Potato starch	22 %	BRIJ35 2%	-
II	Potato starch	22 %	-	5 %
III	Potato starch	22 %	-	10 %





**Fig. 4.** Breaking force average values with standard deviation for samples I, II III (Tab. 1) cut a) parallel and b) perpendicular to the direction of film production

Similar relationships were obtained for the tested material when determining the value of breaking force. Film II, without added emulsifier, turned out to have the greatest resistance to rupture, for both methods of cutting the samples (Fig. 4).

The average force value required to destroy the samples from such material prepared parallel to the direction of film



**Fig. 5.** Examined biodegradable film's thickness for samples I, II, III (see Table 1)

production reaching 8.5 N, while for the perpendicular direction was lower by about 43%. The emulsifier presence in the composition of raw material resulted in a lower tensile strength of the produced material. The increase of water content from 5 % to 10 % in the granules without emulsifier resulted in the reduction of the breaking force (Fig. 4).

For such films, reduction in the value of the breaking force by about 60 % for samples cut in a direction parallel to the direction of film production and more than 40 % for film cut in the perpendicular direction has been observed. In the case of film I that contained the emulsifier in the granules, the observed breaking force values in a direction parallel and perpendicular amounted for respectively 4.78 MPa and 3.0 MPa. The smallest differences in the values of breaking strength were noted in the case of material III without emulsifier with 10 % water content in the granules. 3.39 N and 2.85 N respectively for samples cut in a direction parallel and perpendicular to the film production were needed to rupture the foil III (Fig. 4).

Figure 5 shows the differences in the thickness of the obtained biodegradable film sheets. The material made from granules containing 22 % of glycerol and 5 % of water addition (Table 1) turned out to have the greatest thickness measured with an accuracy of  $\pm$  0.01 mm. This film (II) was also over 1.5 times thicker than containing an emulsifier and glycerin foil I, and about 1.3 times thicker than the third film having in its composition glycerol and 10 % of water addition (Fig. 5).

Mechanical properties of the films determined during the examination showed a correlation between Young's modulus and breaking force values and both: the granular raw material composition and a way of preparing samples. The differences in the values of strength parameters indicate that biodegradable films belong to the anisotropic materials group.

#### CONCLUSIONS

The highest values of Young's modulus in the case of sampling in a direction parallel to the film production were obtained for films produced from the granules with the addition of an emulsifier (205.8 MPa) and for films with 5 % water content in the granules (213.3 MPa). These values were almost twice as high as in the samples cut perpendicularly to the direction of film production.

Doubling of water content in the granules from 5 % to 10 % resulted in the lower values of Young's modulus and breaking force in both directions.

In the case of material cut in a direction perpendicular to the direction of film production in the presence of the emulsifier composition in granular led to obtaining a rupture force values at the same level as at 10 % water content.

Determined, significant differences in the values of strength parameters of the tested material in two perpendicular directions indicate the anisotropic nature of the examined films.

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#### ANIZOTROPOWOŚĆ ODKSZTAŁCEŃ FOLII BIODEGRADOWALNEJ WYTWORZONEJ ZE SKROBI TPS

Streszczenie. W pracy przedstawiono wyniki badań mające na celu sprawdzenie anizotropowego charakteru folii biodegradowalnej wytworzonej ze skrobi ziemniaczanej. Na podstawie testu rozciągania wyznaczono wartości modułu Younga i siły zerwania materiału w przypadku próbek z folii wycinanych w kierunku równoległym i prostopadłym do kierunku jej wytwarzania. Występujące różnice wartości modułu sprężystości podłużnej i siły zerwania w zależności od sposobu preparacji próbki wskazywały na anizotropowy charakter badanego materiału. Porównano również wpływ składu surowcowego granulatu użytego do produkcji folii na jej grubość oraz na wartość wyznaczanych parametrów wytrzymałościowych.

Słowa kluczowe: folia biodegradowalna, anizotropowość, moduł Younga, siła zerwania.

# Method for determining the ventilation air quantity in buildings for cattle on a base of CO<sub>2</sub> concentration

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Summary. Quantity of the ventilation air stream in buildings for cattle can be determined by means of constant concentration of an indicator gas, which requires sophisticated devices for data acquisition. Carbon dioxide emitted by animals may play a function of the indicator gas. The paper presents the method for calculating the ventilation air stream amount in livestock buildings equipped with natural ventilation system. The stream amount can be determined on the basis of measured concentration of the carbon dioxide and air temperature in animal compartment applying the worked out equations. The calculations take into account the livestock density and cow's dairy efficiency.

Key words: livestock building, natural ventilation, air stream, calculation method.

List of symbols:

C – concentration of gas in the air, mg/m<sup>3</sup>

 $C_{co2}$  – concentration of carbon dioxide in the air, mg/m<sup>3</sup> hpu – heat production unit equal to 1000 W of the total heat at temperature 20°C,

m – weight of animals, kg

- M molecular weight, g/mol
- n number of cows in herd, animals
- p pregnancy duration, days

 $t_{\rm w}$  – temperature of internal air, °C

- $\ddot{V}$  amount of ventilation air, m<sup>3</sup>/s
- V molar volume, dm<sup>3</sup>/mol
- $Y_{i}$  daily dairy production, kg
- $\dot{\Phi}_{zc}$  total heat emitted by animals, W  $\Phi_{zc}(t_w)$  total heat emitted by animals at the ambient temperature equal to t<sub>w</sub>, W

### INTRODUCTION

There are different solutions of ventilation systems in livestock buildings depending on required quantity of ventilation air stream, which depends in turn on type of livestock in the building. The main task of the ventilation system consists in removing the harmful gases excess and maintaining the optimum air temperatures in animal compartments [2,7,9,12]. Mechanical ventilation is applied in buildings for poultry due to great needs for air exchange and necessity to avoid excessive dusting, which in consequence could lead to explosive gas mixture formation [8].

Cattle buildings can be equipped with various constructional and functional solutions as well as various devices depending on the herd size and animal husbandry technology [6,15,16,17]. Ensuring the appropriate ventilation in animal compartment is a fundamental condition for maintaining the animal's welfare and high dairy production [3,4,5,13]. Buildings for cattle are most often equipped with natural ventilation system, while chimney ventilation is applied in buildings with relatively small livestock density and utility garret, and natural ventilation with ridge gap is useful in hall-type buildings with no garret. The quantity of ventilation stream depends on a spectrum of factors such as geometric dimensions of the system elements, the air pressure difference between the inlet and outlet, velocity, and direction of winds, as well as air flow resistance (drag) [18]. There is a possibility to some regulation of the stream intensity by means of partial closing the supply or exhaust ventilation holes, which results from different needs for air exchange in summer and in winter.

#### THE AIM OF STUDY

It is possible to determine the true amount of ventilation stream in a livestock building by means of measuring the air flow velocity in a supply or exhaust channel (gap). Mounting the anemometer, particularly in the ridge gap that is placed several meters up, is sometimes difficult, and adjusting the measurement unit perpendicularly to the air flow direction is often completely impossible.

There are also a variety of factors that make such measurement disturbed and result precision biased: strength and direction of winds, uncontrolled air exchange due to doors and windows opening.

The study aimed at presenting the method for determining the quantity of ventilation air stream in buildings for cattle on the basis of carbon dioxide concentration in animal compartment.

# CARBON DIOXIDE CONCENTRATION IN ANIMAL COMPARTMENT

Studies upon microclimate parameters in stanchion barns for cattle indicate that carbon dioxide concentration usually does not exceed the permissible level [14]. This was confirmed by research performed in loose barn localized in Ossowa. Measurements of carbon dioxide concentration and air temperature within animal compartment as well as outer air temperature, were made in winter 2008. The measurement device was set up to measure and register the results at 15-minute intervals. Carbon dioxide concentration oscillated within guite wide range from 400 up to 1500 ppm (Figure 1), whilst it did not exceed the maximum value (3000 ppm). Such large differences in CO<sub>2</sub> concentrations were not the result of the variations in animal's emission, because livestock density was constant. It rather resulted from the changes in the intensity of natural ventilation system operation. The quantity of ventilation air stream varies with time and along with the change of pressure difference between the supply and exhaust. The air pressure difference depends on the height difference (that is constant) and difference between internal and external air temperatures (that varies with time). Dependence of CO<sub>2</sub> concentration in the air in animal compartment is presented on plots (Figure 2).



Fig. 1. Carbon dioxide concentration in loose barn.



**Fig. 2.** Carbon dioxide concentration and difference between internal and external air temperatures.

# METHOD FOR DETERMINING THE VENTILATION AIR STREAM QUANTITY

There are methods for determining the exchanged air stream in a building due to ventilation and infiltration [1]. These are three methods applying the marker gas:

- Marker gas decline method,
- Constant injection method,
- Constant concentration method.

Four types of the marker gas are suitable for measurements of the multiplicity of air exchange: helium, sulfur hexafluoride, nitrogen oxide, and carbon dioxide. However, carbon dioxide cannot be used if the user is present within the measurement zone, because he emits  $CO_2$  as well [PN-EN ISO [22]]. If it is assumed that the livestock density in analyzed period is constant and carbon dioxide emission does not change with time, the carbon dioxide emitted by animals can be considered as the marker gas. In fact, the  $CO_2$  emission depends on animal's activity and ranges within a day [19]. The quantity of carbon dioxide emitted by animals is strictly associated with the amount of heat released. Amount of the total heat produced by dairy cows at the ambient temperature (20 °C) [20,21] equals to:

$$\Phi_{zc} = 5,6m^{0.75} + 22Y_1 + 1,6 \cdot 10^{-5} p^3 \quad \text{W}, \tag{1}$$

Assuming that dairy cattle herd in an animal compartment consists of n animals, mean b&w cow's body weight is 600 kg, and average degree of cow's pregnancy advance is 100 days [Głuski 2009], equation #1 can be written in the following form:

$$\Phi_{zc} = n \cdot (694, 9 + 22Y_1) \quad W, \tag{2}$$

The outer temperature other than 20 °C is taken into account in reference to hpu unit:

$$\Phi_{zc} = 1000 + 4 \cdot (20 - t_w) \quad W, \tag{3}$$

Therefore, the amount of the total heat in the animal compartment  $t_w$  produced by cattle herd consisting of *n* cows is:

$$\Phi_{zc}(t_w) = n \cdot (694, 9 + 22Y_1) \left[ 1 + \frac{4(20 - t_w)}{1000} \right] \quad W, \tag{4}$$

And in more simple form:

$$\Phi_{zc}(t_w) = n \cdot (694, 9 + 22Y_1)(1, 08 - 0, 004t_w) \quad W, \tag{5}$$

The quantity of produced  $CO_2$  amounts to 0.185 m<sup>3</sup>h<sup>-1</sup> in reference to a single *hpu* unit. The dairy cattle herd consisting of *n* animals at the ambient temperature of t<sub>w</sub> would emit the following quantity of carbon dioxide per hour:

$$CO_{2}(t_{w}) = n \cdot 0.185 \cdot 10^{-3} (694, 9 + 22Y_{1})$$
  
(1,08-0,004 t<sub>w</sub>) m<sup>3</sup>h<sup>-1</sup>. (6)

Carbon dioxide is one of the air components and its proportion in clean air is 360 ppm (706.8 mg/m<sup>3</sup>). Permissible CO<sub>2</sub> level in an animal compartment, where dairy cattle is kept, amounts to 3000 ppm (5890 mg/m<sup>3</sup>). The CO<sub>2</sub> concentration in air, as similar as other harmful gases, is measured and expressed in ppm units (parts per million). In order to recalculate the gas concentration from ppm onto mg/m<sup>3</sup>, following dependence can be applied [11]:

$$C = \frac{M}{V_{\nu}} \cdot x \cdot ppm \quad \text{mg/m}^3.$$
<sup>(7)</sup>

Molecular weight of carbon dioxide is 44.01 g/mol, and molar volume is constant for all gases and equals to 22,415 dm<sup>3</sup>/mol:

$$C_{CO_2} = \frac{44,01}{22,415} \cdot x \cdot ppm = 1,963 \cdot x \cdot ppm \quad \text{mg/m}^3.$$
(8)

Carbon dioxide emitted by animals is removed out of the animal compartment by ventilation system. Volume of 1 m<sup>3</sup> of internal air, in which measured carbon dioxide concentration is x ppm, contains x 10<sup>-6</sup> m<sup>3</sup> CO<sub>2</sub>, whereas 1 m<sup>3</sup> of the outer air contains CO<sub>2</sub> quantity corresponding to 360 ppm, i.e. 0.00036 m<sup>3</sup>. Exchanging 1 m<sup>3</sup> of air per hour by means of ventilation, the difference of carbon dioxide between inner and outer air is removed. Because the whole herd emits during an hour the carbon dioxide described by equation #6, the stream of ventilation air V m<sup>3</sup>h<sup>-1</sup> at the moment of CO<sub>2</sub> concentration measurement in internal air, amounts to:

$$V = \frac{CO_2(t_w)}{(x - 360) \cdot 10^{-6}} =$$
  
=  $\frac{n \cdot 0.185 \cdot 10^{-3} (694, 9 + 22Y_1)(1, 08 - 0.004t_w)}{(x - 360) \cdot 10^{-6}}$  m<sup>3</sup>h<sup>-1</sup>, (9)

After simplifications, equation #9 is of the following form:

$$V = \frac{n \cdot 185 \cdot (694, 9 + 22Y_1)(1, 08 - 0, 004t_w)}{(x - 360)} \quad \text{m}^3\text{h}^{-1}, \quad (10)$$

#### CONCLUSIONS

The method worked out during this research makes it possible to determine the quantity of ventilation air stream in buildings for dairy cattle equipped with gravitational ventilation system. The method does not require any sophisticated devices for data acquisition. The procedure for determining the amount of ventilation air stream consists of the following steps:

- Making the measurements of carbon dioxide concentration and air temperature within animal compartment,
- 2. Determining the livestock density,
- 3. Determining the average dairy efficiency in a herd,
- 4. Calculating the ventilation air stream.

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# METODA OKREŚLANIA ILOŚCI POWIETRZA WENTYLACYJNEGO W BUDYNKACH DLA BYDŁA NA PODSTAWIE STĘŻENIA CO2

S tr e s z c z e n i e . Wielkość strumienia powietrza wentylacyjnego w budynkach dla bydła może być określana za pomocą stałej koncentracji gazu - wskaźnika, co wymaga skomplikowanych urządzeń do pobierania danych. Dwutlenek węgla emitowany przez zwierzęta może odgrywać funkcję gazu wskaźnika. W pracy przedstawiono metodę obliczania wielkości strumienia powietrza wentylacyjnego w budynkach inwentarskich wyposażonych w system wentylacji naturalnej. Wielkość strumienia może być określona na podstawie zmierzonego stężenia dwutlenku węgla i temperatury powietrza w pomieszczeniu dla zwierząt, przy zastosowaniu opracowanych równań. Obliczenia uwzględniają gęstość obsady i dzienną wydajność mleczną krów.

Słowa kluczowe: budynek inwentarski, naturalna wentylacja, strumień powietrza, sposób obliczania.

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# The economical and ecological aspects of using the modified water-glass

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Summary. Moulding sands were prepared, using chemically modified water-glass, hardened with diacetate ethylene glycol and CO<sub>2</sub>, and tested for their binding properties. In the case of using of modified chemically water-glass his participation in moulding sands can be diminished about 20% (to 2,0 w.%.). Residual strenght of the moulding sands with modified chemically water-glass in the temperature range to 300 °C is smaller from about 35% to about 60%, in temperatures 500 to 700°C has a nearing value to the residual strength of the moulding sands with not modified water-glass and in temperatures from 700 to 900°C stays practically invariable. The usage of modified chemically water-glass, as binder in the "CO, process", makes possible the increase of the compression strength of the sand mixes samples about 50%, comparatively to the compression strength of the moulding sands, containing 3,0 weight % not modified water-glass.

Key words: moulding sands, water-glass, structure, modification.

#### INTRODUCTION

Soluble sodium silicate (water-glass), along with other binders and technology of casts from ferrous and nonferrous metals, is one of the most popular self-hardening, inorganic binders [18,20-21,23-24,28-29]. Water glass used for over 50 years in foundry industry as binder for cold hardening moulding and core sands is cheap, easily available and nontoxic. However, in comparison to organic binders it has some drawbacks such as higher brittleness, limited knock-out properties of moulding mixtures, more difficult reclamation of the sand grains, as well as insufficient thermal resistance and formation of sinters due to a susceptibility of the Na<sub>2</sub>O-SiO<sub>2</sub> system to react with quartz sand at elevated temperatures. These disadvantages can be limited by producing in the silica gel of organic nets IPN (IntraPenetratingNets) which make reducing amounts of binder in moulding sands and

reducing residual strenght cores and moulds. Modified soluble sodium silicate make possible:

- optimum conditions for hardening of moulds and cores of required physical and mechanical properties,
- reduced strength of cores and moulds within temperatures between 300 and 1200°C, and consequently diminishes labor costs involved with knocking out foundry moulds and cores from castings,

easier reclamation of the sand grains.

These tasks should be developed together, i.e. better mixture properties should be accompanied by improved knock-out proprieties and reclamation capabilities.

Binding properties of sodium silicate solution can be improved by introducing morphoactivators into its structure, to control morphology of the final product. Water soluble high molecular compounds with active functional group such as -OH,  $-NH_2$ , =CONH,  $-CONH_2$ , -COOHand others can be used as modifiers. Modifiers accelerate the process of dissolving solid silicate glass, contribute to the formation of higher adhesive strengths, increase especially cohesive strengths and reduce the brittleness of the mass formed. Their presence in silicate solution can rise its working performance as a cohesive, and reduce its consumption [1-17, 19, 22, 25-27].

It was found that most favourable conditions for chemical modifying sodium silicate solution exist in the process of autoclave dissolving solid sodium silicate glass in water. Hydrated silicate anions pass then continuously into solution and undergo hydrolysis, to form of polysilicate anions and alkali metal cations, simultaneously. The modifiers introduced in this step have a favourable influence on shaping the structure and properties of the silicate binder. Structures with intrapenetrating polymer nets (*IPN*) are then formed, with a consequence that sodium silicate polymer matrix becomes reinforced with organic polymer bonds. Commercial sodium silicate solution is known to possess various chemical composition designated by SiO<sub>2</sub> to Na<sub>2</sub>O molar ratio (*M*), ranging from 2 to 3.3. In the foundry, to manufacture moulding mixtures where esters e.g., ethylene glycol diacetate, are used as hardeners, a product with M = 2,0-2,5 is used, especially that of M = 2,0.

#### PURPOSE AND METHODS

Moulding sands were prepared, using chemically modified water-glass R-145S/MC1,0 and R-150/MC1,0 [8], hardened with diacetate ethylene glycol and CO<sub>2</sub>, and tested for their binding properties. As reference sample unmodified commercial water- glass of R-150 type was used. The amount of binder in the moulding sands accounted to 2,5 weight parts while the hardener represented 15% in relation to the mass of the water-glass. The main fraction of the grains of the used quartz sand was 0.20/0.40/0.32 with homogeneity index 90. At ambient temperature, the specimens prepared were tested for bending strength  $(R_{a}^{u})$ , tensile strength  $(R_{m}^{u})$ , compressive strength  $(R_{u}^{u})$ , and - after baking at temperatures ranging from 100°C to 900°C – residual strength  $R_{r}$ . Permeability  $(P^{u})$  of the samples of investigated moulding sands in relation to hardening time was determined.

#### **RESULTS AND DISCUSION**

Results of research represent on the fig. 1-3. Moulding sands with the participation of modified chemically water-glass R-145"S"/MC1,0 in the quantity 2,5 w.%, possess nearing technological proprieties to the propriety of technological sandmixes with the participation not modified chemically water-glass R-150 in the quantity 2,5 w.%.

In the case of using of modified chemically waterglass R-150/MC1,0 his participation in moulding sands can be diminished about 20% (to 2.0 w.%.). The moulding sands with such participation of water-glass possess sufficient technological proprieties. Permeability of moulding sands with the participation not modified and modified chemically water-glass, have nearing values (from about 420 to about 500 m  $\cdot$  10<sup>-8</sup>/Pa  $\cdot$  s). Residual strength of the moulding sands with chemically modified water-glass R-145"S"/MC1,0 (2,5 w. %) in the temperature range to 300°C is smaller from about 35% to about 60%, comparatively to the residual strength of the moulding sands with modified water-glass R-150 (2,5 w. %). In temperatures 500 to 700°C residual strength of the moulding sands with modified chemically water-glass R-145"S"/ MC1,0 has a nearing value to the residual strength of the moulding sands with not modified water-glass R-150



**Fig. 1.** Strenght proprieties of the samples of the moulding sands with the participation of the different content of chemically modified water-glass R-145 "S"/MC1,0; R-150/MC1,0 and not modified water-glass R-150, with diacetate ethylene glykol as a hardener. Marks on the drawing refer compression strengths after 3 and 24 hours of setting (Rc3, Rc24), bending strengths after 3 and 24 hours of setting (Rm3, Rm24).



**Fig. 2.** Permeability of the samples of the moulding sands with the participation of the different content of chemically modified water-glass R-145 "S"/MC1,0; R-150/MC1,0 and not modified water-glass R-150, with diacetate ethylene glykol as a hardener. Marks on the drawing refer permeability after 3 and 24 hours of hardening (Pu3, Pu24)



**Fig. 3.** Residual strenght of the samples of the moulding sands with the participation of the different content of chemically modified water-glass *R-145* "*S*"/*MC1,0*; *R-150*/*MC1,0* and not modified water-glass *R-150*, with diacetate ethylene glykol as a hardener

(2,5 w. %). In temperatures from 700 to 900°C residual strength of the moulding sands with chemically modified water-glass *R-145"S"/MC1,0* stays practically invariable (about 0,5 MPa), and in the case of the moulding sands with not modified water-glass *R-150* (2,5 w. %) her value surrenders to the enlargement to about 3 MPa. The usage of modified chemically water-glass *R-145"S"/MC1,0* in the quantity 3,0 w. %, as binder in the "*CO<sub>2</sub> process*", makes possible the increase of the compression strength

of the moulding sands samples about 50%, comparatively to the compression strength of moulding sands samples, containing 3, 0 w.% not modified water-glass *R-145*. At the participation in moulding sands of modified chemically water-glass *R-145''S''/MC1*,0 in the quantity 4,0 w.%., the compression strength of moulding sands samples, is nearing to the compression strength of the moulding sands samples containing 6,0 w.% not modified waterglass *R-145* (fig. 4-5).



**Fig. 4.** Strength properties of the samples of the moulding sands (*process CO*<sub>2</sub>) with the participation of the different content of chemically modified water-glass *R*-145"S"/MC1,0; *R*-150/MC1,0 and not modified water-glass *R*-145



Fig. 5. Permeability of the samples of the moulding sands (*process CO*<sub>2</sub>) with the participation of the different content of chemically modified water-glass *R-145* "S"/MC1,0; *R-150*/MC1,0 and not modified water-glass *R-145* 

#### CONCLUSIONS

- The chemical modification of the water-glass makes possible the diminution of its contents in the moulding sands and the improvement of their knock-out properties. This improves economical efficiency of the production in consequence of the material costs decrease, diminishes costs of knocking out and cleaning of castings and improves the efficiency of the regeneration process of the used sands.
- 2. In many cases chemically modified water-glass replace expensive and toxic bindings.

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#### EKONOMICZNY I EKOLOGICZNY ASPEKT STOSOWANIA MODYFIKOWANEGO SZKŁA WODNEGO

Streszczenie. Określono właściwości technologiczne mas formierskich wykonanych z zastosowaniem modyfikowanego chemicznie szkła wodnego utwardzanego dwuoctanem glikolu etylenowego i CO2. Stosując modyfikowane szkła wodne można zmniejszyć jego zawartość w masie formierskiej o około 20% (do 2 % masowych). Wytrzymałość końcowa mas formierskich z modyfikowanym chemicznie szkłem wodnym ma mniejszą wartość od około 35% do około 60% w temperaturze do 300°C, w temperaturze 500 do 700°C ma zbliżoną wartość do wytrzymałości końcowej mas wykonanych z nie modyfikowanym szkłem wodnym, natomiast w temperaturze 700 do 900°C praktycznie nie ulega zmianie. Stosując modyfikowane chemicznie szkło wodne w "procesie CO"" możliwe jest uzyskanie wartości wytrzymałości na ściskanie masy formierskiej większej o około 50%, w porównaniu do wytrzymałości na ściskanie masy formierskiej zawierającej 3% masowych nie modyfikowanego szkła wodnego.

Słowa kluczowe: masa formierska, szkło wodne, struktura, modyfikacja.
# Hierarchy of influence of modern technical solutions used in agricultural tractors on the effectiveness of their work

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Summary. An analysis of the impact of technological and organizational factors on the efficiency of agricultural tractors was made. Importance of modern technical solutions of assemblies used in agricultural tractors was assessed. The study showed that the values of technical and exploitation parameters of the tractor and its availability are more important than the modernity of technical solutions.

Key words: tractor, efficiency, modernity.

#### **INTRODUCTION**

Productivity and operation costs of machine units depend on many factors [14,12,13,15,1]. One of them is the modernity of solutions used in agricultural tractors.

The concept of modernity is widely used in agricultural technology, the more that the offer of innovative solutions is a priority for manufacturers of tractors and machinery. Studies made by Francik (2002) show that farmers require to evaluate agricultural equipment in terms of modernity. In the literature the works of [2,3,4] can be found, which demonstrate how to evaluate modernity of technical - construction solution of different models of tractors using neural networks. However, in the available literature no reports were found on how modern technologies in tractors are important and what impact they have on the efficiency of tractors. Thus, the aim of the study was to prioritize the significance of modern solutions in agricultural tractors with regard to other factors affecting the economic efficiency of their work. Moreover, the assessment was made which will identify the specific technical solutions for which the modernity has the greatest impact on the economic efficiency of the tractor.

# **RESEARCH METHODS**

The set research target was accomplished on the basis of expert knowledge using expert and mathematical method called the Delphi method or a method of Delphi [5].

The Delphi method was developed in the 50s in the U.S. center of strategic studies, the RAND Corporation. Since then, the method has been used repeatedly for such needs as health, defense, business, education, information technology and transport. It also found a permanent place in the foresight programs, among others in Japan, South Korea, Germany, France, Great Britain, Hungary and the Czech Republic [6]. The application of the Delphi method in agriculture is presented in the work of [7,8,9,5].

The course of research procedure according to Delphi method is shown in Figure 1.



Fig. 1. A diagram of the research using expert and mathematical methods

The basic action in this test procedure was the development of special research questionnaires through which the experts gave their opinions on the issues analyzed.

The study questionnaire included two tables in which the experts noted in the numerical values reflecting their assessment. In order to facilitate the evaluation procedure idea of the event tree was used, also called the Isikawa tree [5]. In it the factors that the experts had assessed were put in groups of factors. In this way the Isikawa tree was created by placing group factors as targets of the second order (Table 1), and factors in each group (objectives III order) at a lower level.

Under the principle of Isikawa tree [5] it was assumed that the impact of all groups of factors is 100 percent. Similar to the impact of each factor included in the group. This principle was in force for experts who have expressed their assessment by breaking 100 percent down into individual factors, thus demonstrating their relevance. In this way, the examiner evaluated separately the significance (importance) of group of factors and individually the factors' significance in a group. Ratings assigned by experts in accordance with the principle of the Isikawa tree are called local priorities [5]



Legend: Cele drugiego rzędu: 2nd order targets; Cele trzeciego rzędu: 3rd order targets

# Fig. 2. Event tree diagram (Isikawa diagram)

Information received from the experts in the research questionnaires were entered into the calculation algorithm prepared in Microsoft Excel where the statistical processing according to the principles presented in the literature followed [11,10]. In the first place compliance in assessments given by the experts was analyzed. For this purpose, the concordance coefficient was applied, which in the absence of equal ranks was determined by the formula [11,10].

$$\Theta = \frac{12S}{N_{\rm E}^2 \cdot (b^3 - b)}$$

In the case of the existence of similar ranks the coefficient of concordance was determined by the formula [11,10].

$$\Theta = \frac{S}{\frac{1}{12}N_E^2 \cdot (b^3 - b) - N_E \sum_{i=1}^{N_E} \cdot T_i}$$

where: S-sum of squared deviations of actual values of ranks, Ne-number of experts, b - number of factors evaluated, T i - index of similar ranks The sum of squared deviations of actual values of ranks calculated by the formula:

$$S = \sum_{j=1}^{b} (\overline{r_j} - \overline{r})^2$$

where: rj - the sum of ranks given by the experts, to the j-th factor, r - the arithmetic mean of sum of ranks

$$\overline{r} = \frac{\sum_{j=1}^{b} \overline{r_j}}{b}, \quad (18) \quad \overline{r_j} = \sum_{i=1}^{N^{\circ}} r_{ij}$$

where: rij-rank given by the i-th expert to j-th factor.

Index of similar ranks was calculated by the formula [11,10]:

$$T_i = \frac{1}{12} \sum_{i=1}^p (t_i^3 - t_i)$$

where: p - number of groups of equal series in serialization of j-th expert, ti - number of repetitions of equal series in p-th group.

Concordance coefficient is equal to 1 if all of the ranks given by the experts are the same, and 0 there are no equal ranks.

In order to realize that experts' compliance is not accidental  $\chi$ -square test was used [10,11].

$$\chi^{2} = \frac{S}{\frac{1}{12}N_{E} \cdot b \cdot (b+1) - \frac{1}{b-1}\sum_{i=1}^{N^{*}} T_{i}}$$

If the calculated value of  $\chi^2$  is greater than the tabular  $\chi^2_{tab}$  and concordance coefficient was significantly different from zero, it was concluded that the compliance of the experts' evaluation is not random [10,11]. Moreover, compliance of judgments of experts was assessed using the coefficient of variation calculated by the formula [10,11]:

$$Vj = \frac{g_j}{m} \cdot 100 \quad [\%]$$

where: gj - standard deviation, mj - arithmetic mean of evaluations given by the experts

$$\bar{m}_j = \left(\sum_{i=1}^{N_e} m_{ij}\right) / N_e$$

where: Mij-standadized rate of stature j-th agent designated by the i-th expert

The standard deviation was calculated by the formula:

$$g_{j} = \sqrt{\frac{\sum_{i=1}^{Ne} (m_{j} - m_{ij})^{2}}{Ne}}$$
 for  $N_{e} > 30$ 

According to the literature [10,11] compliance of individual assessments set by the experts was considered sufficient if Vj  $\leq$  0.25. However, Vj values > 0.3 were considered as insufficient compliance.

In case of discrepancies in the assessments of experts the second phase of the study provided for in the Delphic method was carried out. Group of experts was chosen, whose assessment differed significantly from the average grade in the first stage. Then, questionnaires were sent to them, which show the average evaluations of all experts. These experts were to comment on the mean ratings and express their acceptance or rejection. If successful, the assessment given by the expert were replaced by average rating bringing in this way the expert to the mean.

The test procedure take into account the situation in which the examiner would not agree with the ratings presented. In this case, the method assumed an additional interview with an expert in order to obtain explanations and justifications for given ratings. In accordance with the principles of the Delphic method that obtains satisfactory reasons for evaluations discrepancies from the expert provide valuable information that there are experts, for whom the importance of the factors is different than for others.

In this study, experts who missed the evaluation of factor after consulting and obtaining the opinion of the experts agreed with the opinions of other experts.

# **RESEARCH RESULTS**

As a result of research we have obtained assessments of the factors given by 74 experts representing holdings of between 11 to 1,000 acres located in different Polish regions. Farms represented by experts pursued different lines of production: only crop production, only livestock production and the. A vast group was represented by farms with only crop production and multidirectional production.

**Table 1.** The hierarchy of importance of factors in terms of impact on the efficiency of agricultural tractors

	Target name	Sum of weights	Mean	Coef. Of variance
C 1	Modernity of solutions applied in a tractor	207	15,0	0,24
C 2	The size of the technical- operating parameters of the tractor (engine power, traction, etc.)	95	21,8	0,21
C 3	Readiness to operate (reliability, effectiveness of the service, supply of spare parts, etc)	132	21,1	0,21
C 4	Tractor operating conditions (the surface field, terrain, etc.)	281	14,6	0,26
C 5	Skills and experience of the operator	241	15,1	0,22
C 6	The organization of works on the farm	340	12,5	0,23
Conc	ordance coefficient		0,305	

$\chi$ -square criterion	137,25

Source: own study

According to experts, the efficiency of agricultural tractors was affected by such factors as : the size of the technical - operating parameters of the tractor (which can include such engine power, the power of WOM and external hydraulics), and readiness of the tractor to work (the level of which depends on parameters such as: reliability, effectiveness of the service, supply of spare parts, etc.). The influence of such factors as the modern technologies used in tractors, in the opinion of experts is lower than the above factors and also is a factor as important as a factor: the skills and experience of the operator. So one can believe that an important activity in order to increase the efficiency of the tractor is to improve the skills of operators.

<b>Table 2.</b> The hierarchy of the impact on the efficiency	
of agricultural tractors of modernity of individual technica	al
solutions used	

	Target name	Sum of weights	Mean	Coef. Of variance
C 21	Modern technical solutions used in the engine	138	20,11	0,22
C 22	Modern technical solutions used in the drive train (clutch, gearbox, axles)	99	19,92	0,22
C 23	Modern technical solutions used in the PTO system	330	12,67	0,25
C 24	Modern technical solutions used in the hydraulic lift system and external hydraulics.	234	16,12	0,20
C 25	Modern technical solutions used in tractor steering, associated with its operation and control	283	14,67	0,24
C 26	The solutions used in cab associated with the work comfort, control of its operation and work of co- operating machinery, obtaining information on the course of work (performance, time, etc.)	201	16,51	0,25
Concor	Concordance coefficient			
χ-square criterion			170,52	

Source: own study

Analysis aimed to demonstrate which modern solutions in tractor components reflect the influence of modern technologies used in agricultural tractors on the effectiveness of their work has shown that the efficiency of agricultural tractor in the greatest extent depends on the modernity of the solutions used in the engine and drivetrain (clutch, gearbox, axles). Subsequently, the solutions used in cab comfort associated with the work, control the work of co-operation of the tractor and the tractor machinery, obtaining information on the course of work (performance, time, etc.) and modern technologies used in the hydraulic lift system and SCV are significant.

# CONCLUSIONS

The studies show that a modern technical solutions is not the main factor affecting the efficiency of the tractor. A more important factor is the size of the technical and operating parameters and the operational readiness of the tractor. In the opinion of experts the operator's skill is an equally important factor as compared to modernity, implying that training of operators should be an effective way to increase the efficiency of the tractor.

According to experts, modern technology should be introduced to the engine and drivetrain.

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# HIERARCHIA WPŁYWU NOWOCZESNYCH ROZWIĄZAŃ TECHNICZNYCH STOSOWANYCH W CIĄGNIKACH ROLNICZYCH NA SKUTECZNOŚĆ ICH PRACY

Streszczenie. Analizowano wpływ czynników technologicznych i organizacyjnych na efektywność ciągników rolniczych. Znaczenie nowoczesnych rozwiązań technicznych podzespołów stosowanych w ciągnikach rolniczych było oceniane. Badania wykazały, że wartości technicznych i eksploatacyjnych parametrów ciągnika i ich dostępność jest ważniejsza od nowoczesności rozwiązań technicznych.

Słowa kluczowe: ciągnik, wydajność, nowoczesność.

# Impact of agricultural tractors advancement on productivity of selected machine units

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Summary. An analysis of the impact of technical sophistication of tractors on the performance of selected machine units was performed. It was found out that depending on the degree of technical sophistication of tractor with relation to the cooperating units, there is an increase in capacity from about 31 to about 55%.

Key words: tractor, performance, machine units.

#### INTRODUCTION

An important feature of a machine unit is its performance [1,2]. The performance of a machine unit has an impact on the duration and cost of application of agrotechnical activity. Krok and Piotrowski (1985) distinguish the practical performance (Ap), calculated taking into account the overall time utilization of shift (K08). This rate in the structure of the time control change takes into account time losses for reasons independent on the machine (such as meteorological and organizational) [5]. But many writers of materials about selection of agricultural machines such as [4,7] use the operational performance (W07) obtained from the product of theoretical yield (technical) and operating time utilization factor (K07) [4,3,2,7].

Knowledge of operational performance is essential also for the economic evaluations of selection of machines and tractors for the farm. In the literature there are works on optimizing the operation of machine units, which help to increase their productivity [9,10]. However, there is lack of publications on determining the operational performance depending on the degree of technical sophistication of tractors. Determining the impact of technological advancement of tractors on the operating efficiency with the use of the operating time utilization factor (K07) presented in the literature [6] is impossible, because its value does not include changes in the time structure of operating shift that are dependent on the degree of technical sophistication of tractors. There is therefore a need to define correction factors that take into account the degree of technical sophistication of tractors for presented in the literature values of the coefficient of utilization of operating time. The presented need has set the goal of studies that were pursued in the research project of Ministry of Science and Higher Education no. 115 089 639. The purpose of study, whose results are presented below, was to assess the impact technical sophistication of tractors on the practical area performance (operational) of the selected machine units (stubble cultivator, seed drill, generator, sprayer and fertilizer spreader).

Yields were determined for the units cooperating with tractors with power of 60, 86 and 110 kW.

#### **METHODS**

In order to assess the impact of technological advancement in the performance of tractor units it was proposed to introduce to the formula for a correction factor for practical area performance (operational)  $\Delta Apij$ for the particular type of agricultural practices. Correction factor taking into account the relation for the practical area productivity (operational) is as follows:

$$W_{07_{ij}} = 0,36 \cdot b_i \cdot v_i \cdot K_{07_i} \cdot \eta_{v_i} \cdot \eta_{bi} \cdot \Delta A_{p_{ij}}, \qquad (1)$$

where: W07ij – area practical efficiency (operational) of the i-th unit cooperating with a tractor with the equipment corresponding to the j-th scenario [ $h \cdot ha$ -1], b - operating unit width [m], vi – machine operating speed [ $m \cdot s -$ 1], K07i - the utilization rate of shift overall time [-]  $\eta vi$  - the working speed use ratio [-]  $\eta bi$  – operating width utilization factor [-]  $\Delta Apij$  - correction factor taking into account the change in the practical performance of the unit depending on the cooperation with the

	Scenario_1	Scenario_2	Scenario_3	Scenario_4
Engine	Controlled mechanically	Controlled mechanically	Controlled mechanically	Electronically controlled
Gearbox	Manual gearbox (synchronized)	Manual gearbox Some gears shifted (synchronized)		Controlled electro-hydraulically with optionally programmed activities performed automatically (e.g. at turns)
Reverse	no	Controlled mechanically	Electro-hydraulic control	Electro-hydraulic control
Front drive	Controlled mechanically	Controlled mechanically	Electro-hydraulic control	Electro-hydraulic control – possible automatic control
Hydraulic lift	Controlled mechanically	Controlled mechanically	Electro-hydraulic control (via EHR)	Controlled electro-hydraulically with optionally programmed activities performed automatically (e.g. at turns)
External hydraulic system	Controlled mechanically	Controlled mechanically	Electro-hydraulic control	Controlled electro-hydraulically with optionally programmed activities performed automatically (e.g. at turns)
WOM drive	Controlled mechanically	Controlled mechanically	Electro-hydraulic control	Controlled electro-hydraulically – automatically
Differential lock	Controlled mechanically	Controlled mechanically	Electro-hydraulic control	Controlled electro-hydraulically – automatically
HVAC	no,	Tractor is equipped	Tractor is equipped	Tractor is equipped

Table 1. Scenarios of tractor technical sophistication variants

Source: own study

tractor with the equipment corresponding to the j-th scenario [-].

 $\Delta$ Apij coefficient value was calculated on the basis of expert knowledge using expert and mathematical methods (Delphic) and the scenario method. For this purpose, based on the analysis of available in Poland tractor manufacturers offer four scenarios of technical equipment of tractors were developed, reflecting different degrees of technical sophistication (Table 1). These scenarios represent the most common variants of technical sophistication of tractors. Scenarios 1 and 2 correspond to tractors with low-technical sophistication, scenario\_3-average tractors and scenario\_4 - highly sophisticated tractors.

Research organization in accordance with the expert and mathematical methods (Methods Delphic) included the following activities [7]:

- finding the required number of experts
- obtaining the consent of an expert to participate in research and conducting a preliminary interview
- providing the expert with research questionnaire
- acquisition of a study questionnaire from the expert
- preliminary analysis of the research questionnaire to determine the correctness of its filling in (no blank rows, to the compliance of sum of points allocated to parameters, etc.)
- entering the data obtained from the questionnaire to a calculation program
- control of the experts' compliance concerning their assessments

 preparation of the next stage of testing procedures in the event of insufficient experts' compliance

The basic action in the test procedure provided in the mathematical expert method was the development of special research questionnaires through which the experts united their opinions on the issues analyzed.

The task of an expert in the various scenarios was to enter the percentage value reflecting a change in productivity of the tractor during agronomic work listed in the questionnaire (tillage work, sowing grain, mineral fertilizing, chemical protection, agricultural transport) in the variants of more favorable conditions (e.g. large field, the field without rocks, flat ground, the soil is not waterlogged) and in less favorable conditions (e.g. small fields, hilly terrain, rocky fields, marshy soil). The reference point for expert was operating performance in case of use of older generation tractor (equipment and work comfort corresponding to models produced in the 80's). It is worth noting that the K07 coefficients given by [6] were determined in the 80's.

After developing a research questionnaire the group of experts was approached. The group of experts consisted of qualified persons with practical experience in direct contact with machinery (tractors operating or managing the machinery) and evaluating the work of agricultural tractors from economic and agro-technical point of view.

The procedure of forming a group of experts assumed the choice of people, who could boast good economic results and the farm's production resulting from their knowledge. Other features that were taken into account that were less relevant to the knowledge derived but significant in the test procedure were: kindness and willingness to participate in the survey. Experts' competence assessment was made based on the evaluation given by the persons leading the research and expert's self-esteem.

On a scale of 0 to 10 the following expert features were evaluated:

- Practical experience in farm management
- Practical experience in the operation of agricultural tractors
- Knowledge of modern solutions in the construction of tractors and their impact on the effects of the tractor.

The method of deliberate selection of experts was applied. Candidates for the experts were indicated by experts from the industry of agricultural technology (such as journalists, agricultural magazines specializing in agricultural technology, local dealers for agricultural tractors and machinery, ODR workers). After the initial conversation and positive verification of the suitability of a person's expertise with regard to the aforementioned criteria, he or she was included in the list of experts.

The study involved 74 experts attended representing the holding of between 11 to 1,000 acres located in different Polish regions.

Compliance of experts' evaluation was assessed using the coefficient of variation calculated by the following formula [10,11]:

$$V_j = \frac{g_j}{m} \cdot 100 \, [\%],$$
 (2)

where: gj - standard deviation, mj - arithmetic mean given by the experts

$$\bar{m}_{j} = \left(\sum_{i=1}^{Ne} m_{ij}\right) / N_{e}, \tag{3}$$

where: Mij-stature ratio normalized of j-th factor designated by the i-th expert

The standard deviation was calculated from the formula:

$$g_{j} = \sqrt{\frac{\sum_{i=1}^{N_{e}} (m_{j} - m_{ij})^{2}}{N_{e}}}$$
 for  $N_{e} > 30.$  (4)

According to the literature [10,11] it was considered that if  $Vj \le 0.25$ , the compliance of individual assessments appointed by experts is sufficient. If Vj 0.3, compliance were considered to be low.

In case of discrepancies in the assessments of experts the second phase of the study provided for in the Delphic method was conducted. Group of experts was selected, whose assessment differed significantly from the average grade in the first stage. Then, questionnaires were sent to them, which showed the average evaluations of all experts. These experts were to comment on the mean ratings and express their acceptance or rejection. If accepted, the assessment given by the expert was replaced by averages, in this way bringing the expert closer to the mean. The experts to whom questionnaires were sent with an average rating of all experts agreed with the opinions of other experts.

Obtained on the basis of expert knowledge productivity changes were processed later in the test procedure as the value of the correction factors  $\Delta Apij$  for individual agricultural practices with the fact that it was expressed as decimals.

K07 coefficients, necessary for the calculation of operational performance for each treatments were taken from the literature [6]. Based on the literature operating speed and the values of the coefficients of used width and speed were assumed. Working widths were assumed on

Table 2. Characteristics of machine units included in the analysis of performance

Item	Stubble machine	Cultivation-seed machine	sprayer	Fertilizer distributor			
Tractors power 80 HP							
producer	Unia Group	Unia Group	Unia Group	Unia Group			
type	CUT L 2,8X510	ECO 350 I	LUX 1015	MX 1200h			
Operating width [m]	2,8	3	15	30			
Tractors power 117 KM							
producer	Unia Group	Unia Group	Unia Group	Unia Group			
type	ARES T XL 3,0	ECO 550	EUROPA II 4024	RCW 10 000			
Operating width [m]	3	3	24	30			
Tractors power 150 KM							
producer	Unia Group	Unia Group	Unia Group	Unia Group			
type	ARES T XL 4,0	IDEA 2200/3	EUROPA II 4028	RCW 10 000			
Operating width [m]	4	3	28	30			

the basis of the technical data presented by the manufacturer. For tractors of the same group the same set of machines was selected (Table 2).

For fertilization treatments and chemical protection it was assumed that the machines are constantly working on the field and working and liquid fertilizers are delivered means of transport. By adopting this assumption spreaders and sprayers efficiency was calculated based on formula No. 1

For tractors with a power of 110 kW only scenarios 3 and 4 were analyzed, because the market in Poland does not provide tractors with equipment corresponding to scenarios 1 and 2.

The calculated efficiency of machine units cooperating with tractors with technical advancement corresponding to the analyzed scenarios are summarized in Tables 5-7.

The performed analyzes showed an increase in performance depending on the degree of technical sophistication of the tractor. For example, if of cultivation of stubble made with 110 kW power unit demand, it is an increase from 2.57 to 3.98 ha  $\cdot$  h-1. In the case of mineral fertilizers spreader cooperating with a tractor of 110 kW capacity, it is an increase from 18.47 to 26.78 h ha-1 in the case of unfavorable working conditions and the level of 28.26 ha  $\cdot$  h-1 for favorable working conditions.

#### RESULTS

Results obtained on the basis of the Delphic method are presented in Table 3.

CONCLUSIONS

The performed analyses have shown that technical advancement results in increases in the efficiency

Table 3. Changes in performance of machine units depending on the tractor tech advancement scenario

Changes in performance of machine units [	%]	
	Activity performed in less favorable conditions (e.g., small fields, hilly terrain, rocky fields, marshy soil)	Activity performed in favorable conditions (e.g. large field, the field without rocks , flat ground, the soil is not waterlogged)
	SCENARIO_1	
Cultivation works (plowing, harrowing, etc.)	33,60	42,87
Sowing cereals	31,68	40,82
Fertilization, chemical protection	36,25	40,36
Transportation of agricultural products	36,44	40,25
	SCENARIO_2	
Cultivation works (plowing, harrowing, etc.)	41,37	44,29
Sowing cereals	38,55	43,10
Fertilization, chemical protection	39,45	41,90
Transportation of agricultural products	36,88	39,90
	SCENARIO_3	
Cultivation works (plowing, harrowing, etc.)	46,72	51,64
sowing cereals	46,42	50,90
Fertilization, chemical protection	45,08	50,50
Transportation of agricultural products	46,64	50,16
	SCENARIO_4	
Cultivation works (plowing, harrowing, etc.)	48,54	55,51
Sowing cereals	46,46	52,05
Fertilization, chemical protection	45,41	53,46
Transportation of agricultural products	45,03	50,51

Source: own study

Item	Stubble machine	Cultivation-seed machine	sprayer	Fertilizer distributor		
Machine efficiency without correction factor	1,80	1,87	6,41	18,47		
Scenario_1						
Unfavorable work conditions	2,39	2,46	8,72	25,12		
Favorable work conditions	2,57	2,63	8,98	25,86		
Scenario_2						
Unfavorable work conditions	2,53	2,58	8,91	25,67		
Favorable work conditions	2,59	2,67	9,04	26,04		
Scenario_3						
Unfavorable work conditions	2,62	2,73	9,30	26,78		
Favorable work conditions	2,71	2,80	9,62	27,70		
Scenario_4						
Unfavorable work conditions	2,66	2,73	9,30	26,78		
Favorable work conditions	2,78	2,84	9,81	28,26		

Table 5. operational performance of cooperating units of tractors with power of 60 kW [h · ha-1]

Source: own calculations

Table 6. Operating Efficiency of units cooperating with tractors with a power of 86 kW  $[h \cdot ha-1]$ 

Item	Stubble machine	Cultivation-seed machine	sprayer	Fertilizer distributor		
Machine efficiency without correction factor	1,92	1,87	10,26	18,47		
Scenario_1						
Unfavorable work conditions	2,56	2,46	13,95	25,12		
Favorable work conditions	2,75	2,63	14,36	25,86		
Scenario_2						
Unfavorable work conditions	2,71	2,58	14,26	25,67		
Favorable work conditions	2,77	2,67	14,47	26,04		
Scenario_3						
Unfavorable work conditions	2,81	2,73	14,88	26,96		
Favorable work conditions	2,90	2,82	15,39	27,70		
Scenario_4						
Unfavorable work conditions	2,85	2,73	14,88	26,78		
Favorable work conditions	2,98	2,84	15,70	28,26		

Source: own calculations

Item	Stubble machine	Cultivation-seed machine	sprayer	Fertilizer distributor		
Machine efficiency without correction factor	2,57	1,87	11,97	18,47		
Scenario_3						
Unfavorable work conditions	3,74	2,73	17,36	26,96		
Favorable work conditions	3,87	2,82	17,96	27,70		
Scenario_4						
Unfavorable work conditions	3,80	2,73	17,36	26,78		
Favorable work conditions 3,98		2,84	18,31	28,26		

Table 7. Operating Efficiency of units cooperating with tractors with a power of 110 kW [ $h \cdot ha-1$ ]

Source: own calculations

of machine units. Depending on the degree of tractor advancement, the performance increase is 31.68% to 55.51%. The highest values of productivity growth have occurred for the cultivation work, and lower for transportation work. In the case of performing the work under conditions favorable in comparison to the work carried out under less favorable conditions the difference is about 6%. Differentiation of labor units performance, depending on the degree of technological advancement should be taken into account in analyses of cost-effectiveness of purchased tractors. Due to the fact that values of the K07coefficient reported in the literature are outdated at the present time, the authors postulate to include the proposed correction factor in the efficiency calculation.

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WPŁYW ZAAWANSOWANIA TECHNICZNEGO CIĄGNIKÓW NA WYDAJNOŚĆ WYBRANYCH PODZESPOŁÓW MASZYN

Streszczenie. Analizowano wpływ zaawansowania technicznego ciągników na charakterystykę wybranych podzespołów maszyn. Stwierdzono, że w zależności od stopnia zaawansowania technicznego ciągnika w stosunku do jednostek współpracujących, następuje wzrost ich mocy od około 31 do około 55 procent.

Słowa kluczowe: ciągnik, wydajność, podzespoły maszyn.

# The test stand calculations of the research station of sub-atmospheric pressure press with implementation of the finite element method

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S u m m a r y. This article presents the application of CAD systems with the use of the finite element method (FEM) in calculations of parameters of the research station of sub-atmospheric pressure press. The obtained results of calculations have been shown as numerical maps, tabular statements and charts. The proposed method of research shall be practically used for fulfilling orders for the needs of agricultural machinery and device industry, building industry, defense industry.

Key words: computer aided design, finite elements method, contact stress, sub-atmospheric pressure press.

# INTRODUCTION

The test stand of a sub-atmospheric pressure press is intended for laboratory tests of the construction of a press which is used for adhesion process of large-size and multi-ply composite elements. The composite elements are used for production of self-supporting container constructions of various use. The composite wall elements are used for cold store constructions and erecting of farm compartments in agricultural technology.

In this paper, the following problem has been discussed: numerical modeling and strength calculations of the major test station components of the large-size press intended for sub-atmospheric adhesion of multi-ply composite panels and non-standard size constructions. The framework of the test stand functions is based on utilization of a sub-atmospheric effect (vacuum) generated between the suitable shaped surface of the work table and a rubber membrane covering elements of the panels which are to be adhered. It is the value of the sub-atmospheric pressure generated which plays the most important role in admissibility of the holding down degree of the adhered elements of a multi-ply panel. The sub-atmospheric effect is output within implementation of a correctly selected vacuum pump which sucks the air off the space between the work table and the rubber membrane.

The work over the project on the test stand calculations of a sub-atmospheric pressure press has been co-supported financially by the European Regional Development Fund within frames of the Innovative Economy Programme.

Within the limits of the realized work, a digital model (3D) of the press has been made, with implementation of a solid modeling method of the CAD systems. Over the next stages of the assigned work, strength-stiffness calculations of the major components and parts constituting the supporting structure of the test stand with utilization of calculating instruments of the CAD systems (a frame analyzer, a finite element method) were done. The final effect of this work was the press test stand construction which enables verification of numerical calculations based on empirical research.



Fig. 1. The test stand of the sub-atmospheric pressure press - practical realization

# THE DIGITAL MODEL OF THE SUB-ATMOSPHE-RIC PRESSURE PRESS WORK UNIT

The digital model of the construction of the subatmospheric pressure press test stand has been completed in the 3D Autodesk Inventor modeling technology. The model contains all the features of the real object (to the scale): geometric, material and dynamic ones. The characteristics of these constructive features have been defined in two aspects - both qualitative and quantitative.

The major element of the digital model of the subatmospheric pressure press work unit is the frame, designed of structural steel sections.

The inter construction of the supporting frame latticework was made of beams, welded perpendicularly to the frame side members. Perpendicularly to the outer beams and the inter beams, two-row-placed struts were welded; the struts were welded in a particular way so that they make, together with the frame side members and the cross-bars, a uniform surface on which work panel unit was placed.

The model of the work panel of the sub-atmospheric pressure press was placed on the leveled surface of the supporting frame. This model consists of two layers of laminated panels arranged in a particular way so that the bonds of the lower layer were placed in the scope of axes of the inter beams of the supporting frame and in crosswise axes of the upper layer of the laminated panels. The prop steel legs, which were allocated in three rows, bear the supporting frame of the sub-atmospheric pressure press.

The air-duct, which was modeled with suitably matched structural sections and joined with use of welding technology, was the further constructional element of the digital model of the test stand.

The rubber membrane is a complement to the subatmospheric pressure press work unit. The membrane (a rubber oilproof plate) whose dimensions are longer than length and width of the work table is intended for air-tight closure of the sub-atmospheric pressure chamber in which the whole adhesive process is completed. The dimensions of the membrane are dependent on the height of the adhered elements.

Completion of the digital model of the sub-atmospheric pressure press work unit has been the basis for MES strength calculations.

# THE MES STRENGTH CALCULATIONS OF THE PRESSURE PRESS WORK UNIT

To obtain calculations of forces which are loading the frame of the pressure press work unit, the MES method was applied (the finite element method). Creation of the model of cooperation of a unit of components (a steel frame, panels, a multi-ply composite panel, a rebate, a rubber membrane), taking contact stresses between deformable objects into account, was the central objection to the main stage of assigned work. This task was put into practice by modeling the contact zone with application of the "surface-to-surface" method in the following steps:

- creation of the geometrical model of the discussed object,
- selection of the material characteristics,
- definition of the contact zone,

- assignment of the contact type,
- creation of the finite element network,
- application of the boundary conditions,
- realization of the calculations,
- analysis of the calculation effects assignment of the reactive forces which are loading individual elements of the frame.

The analysis of the deformable body contact belongs to nonlinear problems, and usually requires considerable analytical inputs and an efficient numerical model of the model being researched. The contact zone is not exactly known and depends on the following factors:

- loading,
- material characteristics,
- boundary conditions.

The contacting surfaces of the bodies can come into interaction and lose it in unpredictable way. Friction is an additional factor which introduces nonlinearity and it can also produce difficulties in convergence of an iterative process. There are three basic ways of realization of this contact:

- node-to-node,
- nod-to-surface,
- surface-to-surface.

To obtain the strength analysis of the unit, arranged in a particular way as board-rebate-composite panel- rubber, the "surface-to-surface" method was applied. The Autodesk Inventor System, working in automatic mode, detected 138 contact pairs between particular elements in the digital model. All the contact pairs were qualified by the system as "bound".



**Fig. 2.** Sample of a bonding (an adhesive-joint-model) between two chip panels

The digital model was subdivided into 227 259 elements, in which 466 848 nodes were separated. The number of the elements was determined by the iterative process of the network consolidation, which was carried on up to the moment when successive steps of the consolidation did not change the value of the calculated stresses.



Fig. 3. The detailed section of the work unit with the finite element subdivision

The boundary conditions were defined by application of loading values to the system and by determination of the bearing props (a place and kind). The loadings were defined by application of working pressure values for selected surfaces of the press work unit.

The 400 hPa sub-atmospheric working pressure, used for the adhesive process, was put on the surfaces of the inter elements of the press work unit, on the contrary, the 1000 hPa atmospheric-corresponding pressure was put on the surfaces of the outer elements.

The bonds (deprivation of degree of freedom of the unit) were put on the surface of the contact of the press frame with the lower surface of the chip panels. 55 permanent bonds for the contact surface of structural sections of the press frame with the lower surface of the laminated chip panels were generated. For surfaces, margins or tops, the bonding of permanency was used. The bonding of permanency eliminates all degrees of freedom between selected components, which is in concord with technology of adhesion of the lower chip panel layer to the upper surface of structural sections which constitute the carrying frame of the sub-atmospheric pressure press.



Fig. 4. The detailed section of the work unit press - a view of pressures applied

For the needs of further research on the digital model of the prototype press, in the whole scope of the MES calculating process, basic values which enable to carry on the strength analysis of particular elements of the press were registered. Strength values, reduced in agreement with the von Mises (Huber) hypothesis, were determined. The strength values had been settled on by the computer system, according to the following relation:

$$\sigma_{red} = \sqrt{\frac{\sigma_x^2 + \sigma_y^2 + \sigma_z^2 - \sigma_x \sigma_y - \sigma_y \sigma_z - \sigma_y \sigma_z - \sigma_z \sigma_x + 3\tau_{xy}^2 + 3\tau_{yz}^2 + 3\tau_{zx}^2}$$

where:

 $\sigma_x$  – the component of a vector of normal stresses along with the X-axis of the accepted frame of reference,  $\sigma_y$  – the component of a vector of normal stresses along with the Y-axis of the accepted frame of reference,  $\sigma_z$  – the component of a vector of normal stresses along with the Z-axis of the accepted frame of reference,  $\tau_{xy}$  – the component of a vector of tangential stresses in the XY plane of the accepted frame of reference,  $\tau_{yz}$  – the component of a vector of tangential stresses in the YZ plane of the accepted frame of reference,

 $\tau_{zx}$  – the component of a vector of tangential stresses in the ZX plane of the accepted frame of reference.



Fig. 5. The distribution of stresses in a layout of chip panels

Table	1.	The	summary	of the	calcu	lation	results	of	the
reduced	stre	esses							

The name of the element	The value of maximal reduced stresses $\sigma_{_{red}}$ [MPa]
chip panels	0,1910
steel rebate	28,0100
composite panel	0,0534
rubber membrane	1,5590

The minimal value of the factor of safety was: 7,39; in connection with the above, the strength condition, with reference to the whole unit, has been fulfilled.

# THE DIGITAL MODEL OF THE SUB-ATMOSPHERIC PRESSURE PRESS FRAME UNIT

The condition for the strength analysis of the construction of the frame unit of the test stand of the subatmospheric pressure press was completion of its digital model. The model has been completed with implementation of the "generator of frames" module of the Autodesk Inventor system. The basic carrying element of the subatmospheric pressure press prototype is the steel frame made of 55 steel structural sections.

With help of the "frame analyzer" module set in the AutoDesk Inventor system, the skeleton model of the frame was generated; the model consisted of 174 nodes and 64 stiff bonds between the bends. The bends were put out at the end of all the structural sections constituting the frame. The stiff joints between the nodes correspond to the welded joints which were configured in the digital model of the frame. The frame unit was supported with 51 permanent hinge props, whose allocation corresponds to the position of the prop steel legs bearing the press. In the nomenclature of the Autodesk Inventor system, these props are named "fastened bond". The way the fastenings are allocated is shown in the picture below.



Fig. 6. The digital solid model of the frame unit of the subatmospheric pressure press



Fig. 7. The digital model of the frame with its nodes

The loading of the construction of the frame unit is originated in the weight-pull force of the particular beams; they come into existences as a result of interaction of the panels-rebate-composite-rubber membrane unit. The other type of interaction considers the bare weight of the particular elements of the work press unit and additional stresses which arise when working sub-atmospheric pressure is implemented. The summary calculations of the beam loading were carried on for the 400 hPa working pressure. It is a presumed working sub-atmospheric pressure which is required in the technological process of adhesion of composite ply materials.

The remaining values of loading for the particular beams (continuous loading and moments of forces) were determined with use of the MES analysis of the press work unit. Values of components of vectors of forces and moments were adjusted to the orientation of the co-ordinate system; the co-ordinates connected with the digital model of the frame unit.

# THE STRENGTH CALCULATIONS OF THE SUB-ATMOSPHERIC PRESS FRAME UNIT

The continuous loading of the Q type (components: Qx, Qy, Qz), was implemented to the upper planes of

the sections constituting the frame unit; the loading was determined in the MES calculations. The vectors of moments of the M type (components: Mx, My, Mz) were additional outer loading.



Fig. 8. The visual view of the outer loading implemented to the sections of the frame unit

After the strength calculations of the frame were carried out, the value of reaction, in the points where the frame unit is supported, was determined. Sequencing further, the maximal value of relocation, defined by a computer system, was determined. The determined value met the requirements of permissible limits which are provisioned by technological conditions of adhesive process.



Fig. 9. The layout of the frame unit relocations

The distribution of normative stresses Smax existing in the maximally loaded beam of the frame unit is shown in the picture below. The maximal stress value was 66,65Mpa, which is a value far smaller than the yield point of the material used in this construction.

In progress of the realized MES calculations of the digital model of the test stand of the sub-atmospheric pressure press, the results meeting all the basic strength indicators and the operational criteria were obtained. The maximal relocation of the construction did not exceed the admissible values, specified by the operational requirements for the sub-atmospheric pressure. On the contrary,

the maximal normal stresses in the beams of the carrying frame was far smaller than the yield point (the calculated factor of safety exceeds the 7,0 value). The numerical analysis indicated that the construction operated with the 400 hPa working sub-atmospheric pressure meets both the operational requirements and the conditions of strength.



Fig. 10. The layout of reduced stresses in a selected beam of the carrying frame

# VERIFICATION OF THE OBTAINED RESULTS OF CALCULATIONS

The test stand was built in the Production of Building Components Firm "Container" - LLC in Plock, Poland based on the digital model of the sub-atmospheric pressure press. Experimental research on realization of the adhesive process of large-size composite panels was completed. The results of the numerical calculations were acknowledged by the empiric research. The construction met both the presumed criteria of strength and stiffness. The press deformations, during realizing the process of technological adhesion of panels, did not exceed the admissible values, do to this fact, the desired geometry of large-size and multi-ply composite objects was performed.



**Fig. 11.** The composite panel produced with implementation of the vacuum adhesion technology

### CONCLUSIONS

The obtained results of calculations have been shown as numerical maps, tabular statements and charts. The analysis of the theoretical calculations proved that they meet the results obtained by means of the empiric research conducted in the Production of Building Components Firm "Container" - LLC in Plock, Poland. Practical implementation of the CAD systems and the MES calculations into the issue presented and discussed in this paper gives useful advantage in the following questions:

- considerable reduction of the time needed to conduct research, due to the numerical analysis of many alternatives of the press,
- relief given to a research unit from routines and uncreative activities,
- undertaking veracious research with application of computer systems -
- just at the stage of the press design,
- ability to perform the numerical analysis of press functioning for cases dealing with adhesion of many types of composite elements differing in both the geometry and the layered structure.

The proposed method of research shall be practically used for fulfilling orders for the needs of agricultural machinery and device industry, building industry, defense industry.

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# OBLICZENIA STANOWISKA BADAWCZEGO PRASY PODCIŚNIENIOWEJ Z ZASTOSOWANIEM METODY ELEMENTÓW SKOŃCZONYCH

S tr e s z c z e n i e . W artykule przedstawiono zastosowanie systemów CAD i metody elementów skończonych do obliczeń stanowiska badawczego prasy podciśnieniowej. Uzyskane wyniki obliczeń przedstawiono w postaci map numerycznych, zestawień tabelarycznych oraz wykresów. Zaproponowana metodyka badań zostanie praktycznie wykorzystana do realizacji zleceń dla potrzeb przemysłu maszyn i urządzeń rolniczych, budownictwa oraz przemysłu obronnego.

Słowa kluczowe: komputerowo wspomagane projektowanie, metoda elementów skończonych, naprężenia kontaktowe, rozkład naprężeń w glebie, prasa podciśnieniowa.

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# **CFD Modeling of Complete Thermal Cycle of SI Engine**

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S u m m a r y. The results of the modeling of thermal cycle of spark ignition internal combustion engine are presented. The modeling was carried out in the AVL Fire. The authors undertook an effort to generate a complete mesh for the test engine, including the intake and exhaust ports and the valves. This involved four computational domains generating. The number of computational cells of engine geometry was optimized. There was included a local and temporary thickening of the mesh which has contributed to more accurate solutions and shortening of computing time and, consequently, the engine cycle calculations.

Key words: engine, simulation, modeling, combustion.

# INTRODUCTION

Engines are designed to maximize power and economy while minimizing exhaust emissions. This is due to growing concern for decreasing energy resources and environmental protection. For this reason, there is still carried out intensive research and development in internal combustion engines. An engine should operate with the greatest efficiency with the least toxic compound emissions. Researches on how to improve the combustion process, introduce a new fuel such as hydrogen, and optimize engine parameters are still carried out. Maximizing the performance of the engine (BMEP) usually causes the occurrence of the so-called knock combustion. Therefore, intensive researches and development in internal combustion engines are being conducted.

Researches based on numerical simulations using advanced mathematical models have recently been developed very intensively. The development of numerical modeling is heightened by increasing computational power that allows modeling not only of flow processes but also combustion in 3D [1,2,3]. One of more advanced numerical models used for combustion process in internal combustion engines modeling is AVL FIRE [4]. In 2009 Institute of Internal Combustion Engines and Control En-

gineering of Czestochowa University of Technology began University Partnership Program with AVL Company. This allowed the use of the Fire software to IC engine thermal cycle modeling [5,6,7]. The AVL FIRE software belongs to programs which are used to modeling of thermal cycle of internal combustion engines. FIRE allows the modeling of flows and thermal processes occuring in the intake and exhaust manifold and in combustion chamber of internal combustion engine. This program allows modeling of the transport phenomena, mixing, ignition and turbulent combustion in internal combustion engine. Homogeneous and inhomogeneous combustion mixtures in spark ignition and compression ignition engine can be modeled using this software as well. Kinetics of chemical reactions phenomena is described by combustion models which take oxidation processes in high temperature into consideration. Several models apply to auto ignition processes. AVL FIRE allows modeling knock process which occurs in combustion chamber of IC engine. This program allows to create three-dimensional computational mesh, to describe boundary conditions of surfaces and initial conditions of simulation, as well.

#### NUMERICAL MODEL

The test engine was constructed on the basis of a fourstroke compression-ignition engine 1HC102 manufactured by "ANDORIA" Diesel Engine Manufacturers of Andrychow. After some constructional changes, this engine was redesigned for the combustion of gasoline as a spark-ignition engine. For this reason, the engine was equipped with a new fuel supply system and an ignition installation. As a result of modernization the shape of the combustion chamber and the compression ratio was reduced from 17 to 8.5. This is a stationary engine, equipped with two valves with horizontal cylinder configuration. The engine is equipped with a cooling system based on the evaporation of liquid.

Figure 1 shows the modernized combustion chamber with spark plug location of the test engine. On the basis of the test engine geometry the computational mesh was created (Fig. 3). Valve lifts curves were determined by measuring the engine cams. The modeling takes into account only the intake and exhaust channels located in the engine head.

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1 8	h.	Ι.	Main	engine	parameters
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bore cylinder	100 mm
stroke piston	120 mm
connecting rod length	216 mm
direction of cylinders	horizontal
squish	11 mm
compression ratio	8.5
engine speed	1500 rpm
number of cylinders	1





The computational mesh can be obtained as surface or volume discretization. In AVL Fire the Finite Volume Method (FVM) is used to calculate the heat flows. For four-stroke engine four computational domains are required. The first domain includes the intake stroke until closure of the intake valves. The second domain is used since the closure of the inlet valve until the exhaust valve timing, at a time when the valves are closed. The third domain is used since the opening of the exhaust valve to the end of the exhaust stroke. And finally the fourth domain is required for the whole engine cycle. The division cycle of three domains eliminates the problem of return flows in the crevices between the valve train and valve seat.

The first step is to draw the engine workspace (Fig. 2). Due to software, valves must be slightly open. This ge-

ometry is loaded into the preprocessor of Fire program. On the basis of this geometry the computational moving mesh is generated (Fig. 3).



Fig. 2. Geometry of engine in CAD





**Fig. 3.** Computational mesh of engine, a) intake, b) compression, c) exhaust, d) complete mesh

The computational mesh around valves was concentrated to obtain more accurate results. Fire gives the possibility of temporary thickening of the grid.

Modelling of the thermal cycle of the test spark ignition engine in the AVL FIRE [4] software was carried out. Modelling of combustion process was carried out using an advanced combustion model. ECFM (Extended Coherent Flame Model) model was used based on the basis of turbulent mixing zone of air, fuel and exhaust. The ECFM was developed in order to describe combustion in spark ignition engines. This model allows the modelling of the combustion process of air-fuel mixtures with EGR effect and NO formation. The model is based on the description of unburnt and burnt zones of the gas. The concept of combustion model is based on a laminar flamelet idea, whose velocity and thickness are mean values, integrated along the flame front. The thickness of the flame front layer depends on the pressure, temperature and content of unburnt fuel in the fresh zone. In addition, it is assumed that reaction takes place within relatively thin layers that separate the fresh unburned gas from the fully burnt gas. This model uses a 2-step chemistry mechanism for the fuel conversion. Unburnt gas phase consists of 5 main unburnt species: fuel, O<sub>2</sub>, N, CO, and H,O. After the burnt gas phase it is assumed that no fuel remains. The burnt gas is composed of 11 species, such as O, O<sub>2</sub>, N, N<sub>2</sub>, H, H<sub>2</sub>, CO, CO<sub>2</sub>, H<sub>2</sub>O, OH and NO.

Tab.	2.	The	main	input	parameters
					1

ignition advance angle	12 deg
fuel	gasoline
fuel temperature	320 K
initial pressure	0.085 MPa
initial temperature	365 K
excess air factor	1.0
density	1.19 kg/m <sup>3</sup>

# RESULTS

As a result of numerical analysis a number of characteristic quantities of combustion process in the engine were obtained such as: pressure, temperature, parameters of flow field, turbulence, heat transfer, species, toxic parameters and others.



Fig. 4. Pressure, heat release rate and accumulated heat release courses



Fig. 5. Cross sections of the engine cylinder during intake stroke - velocity field with streamlines



Fig. 6. Cross sections of the engine cylinder at the beginning of combustion and during exhaust stroke - temperature

Figure 4 shows pressure and heat release rate, and accumulated heat release courses. The values of these parameters are realistic, and these are close to parameters obtained by real engine indications. The publication does not present the analysis results of the engine thermal cycle, and is only capable of modeling a complete engine cycle. The results of the analysis will be presented in subsequent publications of the authors.

In Figure 5 the flow field in the modeled engine during intake stroke is presented. The main swirl process by the streamlines is underlined. There, the so-called tumble swirl is visible. This swirl is responsible for flame kernel direction propagation.

Figure 6 shows the cross sections of the engine cylinder where the temperature field is presented. The first two pictures show flame propagation in the combustion chamber. The direction of flame propagation is determined by fluid flows generated during intake stroke (Fig. 4). In Figure 4 the tumble flow is highly visible. The second two pictures show the exhaust stroke when the exhaust valve starts to open and when it is full open.

# CONCLUSIONS

AVL FIRE program is a research tool that can be successfully used to model the thermal cycle of the internal combustion engine. The AVL FIRE up-to-date numerical code used during research made possible to generate 3D geometric mesh of combustion chambers of the test engine and allowed to perform numerical calculations of processes occurring in this engine. Simulations of combustion process have delivered information concerning spatial and time-dependent pressure and temperature distribution in combustion chamber. This information would be extremely difficult to obtain by experimental methods. It allows analyzing not only the combustion chamber but also the intake and exhaust process.

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Commission of Motorization and Power Industry in Agriculture VIII/2008.

# MODELOWANIE PEŁNEGO CYKLU CIEPLNEGO SILNIKA ZI

S tr e s z c z e n i e. W pracy przedstawiono wyniki modelowania obiegu cieplnego tłokowego silnika spalinowego o zapłonie iskrowym. Modelowanie przeprowadzono w programie AVL Fire. Autorzy pojęli trud wygenerowania kompletnej siatki dla posiadanego silnika spalinowego, z uwzględnieniem kanałów dolotowych wraz z zaworami. Wymagało to wygenerowania czterech domen obliczeniowych. Dokonano optymalizacji ilości komórek obliczeniowych siatki geometrii silnika. Uwzględniono miejscowe i chwilowe zagęszczanie siatki, co przyczyniło się do uzyskania dokładniejszych rozwiązań oraz skrócenia i tak długiego czasu obliczeń cyklu silnika.

Słowa kluczowe: silnik, symulacja, modelowanie, spalanie.

# Quality of operation of bauer rainstar 90/300 reel sprinkling machines in agrocoop imel sa agricultural company

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Summary. The paper aimed at evaluation of the results of sprinkling uniformity measurements for four reel Bauer Rainstar 90/300 sprinkling machines, realized during three years on the lands of agricultural company Agrocoop, Imel'. The sprinkling rate uniformity was evaluated with the use of general indexes for irrigation technique work quality. Value of the uniformity coefficient was determined according to STN ISO 7749-2 Standard. There were used from 30 to 70 measuring cups, spaced by 1 to 2 m. Particular sprinkling rate values ranged from 0.41 mm to 49.16 mm, while average values ranged from 15.19 to 31.60 mm. Satisfactory values of sprinkling uniformity coefficients CU according to Frielinghaus and Růžička criterion (more than 70 %) were obtained for three sprinkling machines during sprinkling without overlapping (CU<sub>21</sub>=72.72%, CU<sub>23</sub>=73.32%, CU<sub>24</sub>=73.23%). The requirements of Klement and Heinige criterion (CU more than 80%) were satisfied for three sprinkling machines (Z1, Z2, Z4), only when overlapping was introduced. None of the investigated sprinkling machines satisfied the requirements of STN ISO 7749-2 Standard (CU above 90%), even when overlapping was applied.

The lowest value of variance coefficient was found for sprinkling machine Z3 (33.29 %), while the highest value for sprinkling machine Z2 (41.31 %); the sprinkling overlapping was found as an effective factor.

Key words: quality of operation, sprinkling, coefficient of sprinkling uniformity CU.

### **INTRODUCTION**

Setting of sprinkling rate values is the first step towards determination of sprinkling uniformity. Therefore, the well-known methods are used that are common in the evaluation of operational quality of irrigation technology.

The applied measuring methods depend on kind of devices used: sprinkling machines with spaced sprinklers, machines with hoses of wide pivot angle or sprinkling machines with reel devices [9,4].

Sprinkling was executed upon decrease in the actual soil moisture content under conditions of hydrolimit value and reduced access to water. Such conditions call not only for soil moisture monitoring but also for controlling of tractors' traction properties in the field [17,19,15,2,78].

During sprinkling, the reel sprinkling machines with sprinklers move continuously along the field. In practice, the sprinkling rate measured on elementary surfaces does not consider the effect of other input factors (sprinkler model, jet diameter, water pressure, sprinkle sector, speed of movement, spacing of sprinklers) [9].

The sprinkling quality is regarded from the viewpoint of correct intensity and uniformity. The sprinkling intensity means the water amount in mm supplied in time unit. The sprinkling uniformity depends on the correct functioning of sprinklers and, particularly, on correct selection of sprinkler jet, water pressure in the flow line and appropriate selection of spacing and reach of the next sprinkler position [11].

#### PURPOSE AND METHODS

The aim of the presented paper was to evaluate the results of sprinkling uniformity measurements for four Bauer Rainstar 90/300 reel sprinkling machines Z1, Z2, Z3, Z4.

The practical measurements were executed during three years in the agricultural company Agrocoop a.s., Imel', situated in the southest Slovakia in Komárno region, with rather flat fields of slope ranging from  $0 - 2^{\circ}$ .

The company uses 30 reel sprinkling machines of model Bauer Rainstar 90/300 (Fig.1); four of them were randomly selected.

	Specifications	
•	Hose diameter and length	90 mm / 300 m
•	Maximal belt length	340 m
•	Flow rate	$17 - 65 \text{ m}^3.\text{h}^{-1}$
•	Connecting pressure	0,35 – 1 MPa
•	Jet size	16 – 30 mm
•	Weight with hose and water	3270 kg
•	Weight with hose and without wat	er 1850 kg
•	Total length with stand	5350 mm
•	Maximal width at greatest spacing	g 2050 mm
•	Total height	3060 mm

The sprinkling machine was equipped with the sprinkler SR-101 of jet diameter 20 mm. The sprinkling machine was controlled with microcomputer Ecostar 4000. The sprinkling uniformity evaluation was carried out on a parcel of land with potato crop.



Fig. 1. Sprinkling machine Bauer Rainstar 90/300 TX Plus Ecostar 4000 with sprinkler SR101

The sprinkling equipment was controlled with buttons on the panel. The system was equipped with sprinkling belt length detector, electronic panel, winding speed detector, solar collector and detector of electric energy source connector. Ecostar 4000 has four lines' display and it shows the settings of machine working parameters. They are: winding speed, time to the end of sprinkling, length of the moved out hose, prior irrigation (irrigation at the beginning before the start of stand movement)

and after irrigation (irrigation at the end of irrigation after the stop of stand movement). The irrigation rate, or more precisely the winding speed, can be adjusted during sprinkling to obtain the so called variable sprinkling rate within one pass of machine.

The most advanced method for sprinkling uniformity evaluation involves application of uniformity coefficient CU, according to CHRISTIANSEN (1942) in [18]:

$$CU = 100. \left[ 1 - \frac{\sum_{i=1}^{n} |h_i - h_m|}{n.h_m} \right],$$
 (1)

where:  $h_i - rainfall$  height on elementary surfaces (mm),

 $h_m$  – average rainfall height on the examined surface (mm),

n - number of elementary surfaces making up the sprinkled surface, equal in size (pc),

 $\sum_{i=1}^{\infty} |h_i - h_m| - \text{absolute sum of variance of average}$ rainfall

Measurements of sprinkling uniformity is evaluated according to STN ISO 7749-2 Standard for the reel sprinkling machines and must be performed on a flat ground (maximal gradient 1%). The winding velocity cannot exceed 1.5 m.s<sup>-1</sup> during investigations; overlapping values of 4, 8 and 16 m are applied in determination of the uniformity coefficient CU (%).



Fig. 2. Spacing of measuring cups in one radius, position of irrigators (rainfall cups, sprinkler, sprinkler movement direction)

### **RESULTS AND DISCUSSION**

The layout of practical measurements is presented in Fig. 2, while the input values for work quality evaluation of the selected reel sprinkling machines together with calculated values of uniformity coefficient according to Christiansen CU are listed in Table 1. As it is evident from the results, the highest value was found for the reel sprinkling machine Z3 and the lowest one for the machine Z2.

Many experiments aimed at investigating the connection between irrigation irregularity and crop. [1,12] independently came to conclusion that plants were equal with respect to sprinkling irregularity. Frielinghaus [3] confirmed it and found the Christiansen uniformity coefficient value equal to 70% as satisfactory one. The measurement accuracy is negatively affected by wind activity, pressure variation in the distributing main and the like [20].

Table	1.	Sprinkling	uniformity,	overlapping = 0
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Sprinkling machine	Cups spacing, m	Aver. Vi, mm	Sum Vi, ml	Sum Vi, mm	CU, %
Z 1	1	15.19	10383	1063.46	72.72
Z 2	1	23.77	14158	1450.10	67.57
Z 3	2	24.18	7082	725.36	73.32
Z 4	2	31.60	9256	948.03	73.23

It was found out that 75% of investigated sprinkling machines achieved the satisfactory uniformity. Therefore, there is a need for further investigations to determine the ways for increasing the uniformity coefficient CU. One of them is overlapping with the next sprinkling belt, for example. The values of sprinkling uniformity coefficient CU at covering of 4, 8 and 16 m are presented in Table 2 together with work quality performance according to Frielinghaus. The CU values increased at the increased overlapping for sprinkling machines Z1, Z2 and Z4, while for Z3 it increased only for overlapping value of 4 m, and then decreased at bigger overlapping values. The minimal

values of outer cups rainfall increase after application of overlapping and so does the uniformity coefficient value.

Růžička [1996] found out that sprinkling uniformity is maintained at sprinkling uniformity coefficient of 70%. [6] consider the value CU = 80 % as good uniformity, while TNV 754307 Standard recommends the uniformity coefficient value according to Christiansen as CU = 90 % for cross uniformity. The Standard recommends also that 80 % of surface should be sprinkled within the range from 0.85 to 1.15 of the average rate at wind velocity of 2 m.s<sup>-1</sup>.

Klementová and Heinig [6] requirements were achieved only after the introduction of overlapping and only for three sprinkling machines; the recommendations of TNV 754307 Standard [16] (CU higher than 90%) were failed without and with application of overlapping.

 Table 2. Sprinkling uniformity with overlapping, Bauer Rainstar 90/300

Serial	Overlapping,	Sprinkling uniformity CU, %					
number	т	Z1	Z2	Z3	Z4		
1	0	72.72	67.57	73.32	73.23		
2	4	76.79	74.06	76.27	83.50		
3	8	83.68	81.89	73.45	88.39		
4	16	84.15	83.04	71.32	83.89		

One of the first researchers who began to evaluate the sprinkling uniformity was [13]; he followed the rule in sprinkling uniformity evaluation that the maximal intensity of sprinkling should not exceed the double value of minimal one, with the exception of outside zone. He developed isograms (the lines like rainfall heights) on the basis of rainfall heights measurements in the rainfall cups, and he evaluated visually the uniformity as very good, good, satisfactory and bad [9].

The descriptive statistics was introduced to Table 3 for the investigated sprinkling machines Z1, Z2, Z3 and Z4. The average irrigation rate was not equal, but it ranged from 15.19 to 31.60 mm. The measuring cups

 Table 3. Descriptive statistics, measurements 2010, sprinkling machine 1, Bauer Rainstar 90/300

	Value							
Parameter	Sprinkling machine 1	Sprinkling machine 2	Sprinkling machine 3	Sprinkling machine 4				
Average value, mm	15.19	23.77	24.18	31.60				
Divergence max – min, mm	23.15	37.69	31.75	48.34				
Minimum, mm	1.84	0.41	7.17	0.82				
Maximum, mm	24.99	38.10	38.92	49.16				
Sum, mm	1063.46	1450.10	725.36	948.03				
Number, pc.	70	61	30	30				
Level of reliability (95.0%)	1.3	2.51	3.01	4.35				
Variance coefficient, %	35.94	41.31	33.29	36.84				

number amounted to 30, 61 or 70 pc.. Values of particular irrigation rates ranged from 0.41 mm to 49.16 mm. The lowest value of variance coefficient was found for sprinkling machine Z3 (33.29 %) and the highest one for sprinkling machine Z2 (41.31 %).

The graphical evaluation of results for particular reel sprinkling machines Z1, Z2, Z3 and Z4 is presented in Fig. 3.



**Fig. 3.** Irrigation rate, overlapping 0, sprinkling machines Z1, Z2, Z3 and Z4

# CONCLUSIONS

The presented article was focused on the work quality evaluation of four reel sprinkling machines in agricultural company Agrocoop Imel', a.s. The method of Christiansen (STN ISO 7749-2 [14]. Standard, 1999) was applied for evaluation. Its value is affected by a series of external factors like: the shape of sprinkling curve, spacing and the wind effect. One can find on the basis of [10,3] recommendations (the sprinkling uniformity coefficient value over 70 %), that the three reel sprinkling machines met the conditions. The requirements were fulfilled with application of overlapping for all the examined reel sprinkling machines. However, the use of overlapping is effective only to a limited degree, because an increase in overlapping decreases the effective output of reel sprinkling machines. As a result, the time and economic items increase; this may point out at the need for optimization of effective spacing of the sprinklers.

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# OCENA JAKOŚCI PRACY DESZCZOWNI SZPULOWEJ BAUER RAINSTAR 90/300 W PRZEDSIĘBIORSTWIE ROLNI-CZYM AGROCOOP IMEL SA

S tr e s z c z e n i e. Celem badań było przeprowadzenie analizy równomierności opadu deszczowni szpulowych Bauer Rainstar 90/300. Pomiary równomierności opadu przeprowadzono na polach uprawnych przedsiębiorstwa rolniczego Agrocoop, Imel SA na Słowacji. Badania prowadzono w ciągu 3 sezonów agrotechnicznych. Obiektem badań były cztery deszczownie szpulowe Z1, Z2, Z3, i Z4. Współczynnik równomierności opadu był określany według normy STN ISO 7749-2. Liczba używanych kubków pomiarowych, które rozstawiano w odległości do 1 do 2 m, wynosiła od 30 do 70.

Wartości poszczególnych średnich dawek polewowych były w zakresie od 15,19 do 31,60 mm. Zadawalające wartości współczynników równomierności opadu według kryterium Frielinghausa i Růžički (CU powyżej 70%) uzyskano dla trzech deszczowni przy deszczowaniu bez zakładu (CU<sub>z1</sub> = 72,72%, CU<sub>z3</sub> = 73,32% i Cu<sub>z4</sub> = 73,23%).

Wymagania według kryterium Klementovej i Heiniga (wartość współczynnika CU powyżej 80% CU) spełnione były dopiero po zastosowaniu zakładów i to tylko w przypadku trzech deszczowni Z1, Z2 i Z4.

Wymaganiom według normy STN ISO 7749-2, według której współczynnik równomierności opadu powinien mieć wartość powyżej 90%, nie odpowiadały wartości CU uzyskane dla żadnej z badanych deszczowni, nawet po zastosowaniu zakładów. Najniższą wartość współczynnika wariancji uzyskano dla deszczowni Z3 - 33,29%, a najwyższą wartość dla deszczowni Z2 -41,31%.

Słowa kluczowe: jakość pracy deszczowni, deszczowanie, współczynnik równomierności opadu CU.

# Entropy analysis of energy price movement

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Summary. The paper presents a novel method of analysis of energy price movement with use of sample entropy, which is used to measure the complexity or information content of a given data set (time series). This technique is used to verify the efficient market hypothesis. The results show that although the price movement is nearly random, there is a statistically significant difference from a completely random walk.

Key words: energy price, efficient market hypothesis, sample entropy.

# INTRODUCTION

Prices of fossil energy sources are crucial for the energy industry and the economy of countries, regions and the world. The crude oil cost increase observed over the last few years has been a challenge not only to individual consumers but even more, to companies whose economy is highly dependent on the cost of energy. In the crisis conditions there is a need to find new approaches towards increasing the efficiency of finance management [12]. The energy cost has a great impact on people life quality: International Monetary Fund estimates that a crude oil price growth of 5 USD per barrel results in economy development rate decrease by 0.3 % [16]. Increasing fuel costs result in increased production costs in the whole industry, especially in agriculture [17].

Another group of people interested in crude oil price behavior are investors, who try to profit from price movement. Recently, many internet-based trading platforms have been made available to individual investors, who can implement their trading strategies easily. For all the groups: individual investors, institutional investors and company management, to be able to forecast the future cost of energy means profit. With this in mind, the author would like to look at the efficient market hypothesis, which in general states, that the price of a given asset responds quickly and accurately to relevant information, so that the future price is unpredictable [3].

The classical definition of market efficiency from 1976 by Jensen is as follows: A market is efficient with respect to information set  $\Omega_{t}$  if it is impossible to make economic profits by trading on the basis of information set  $\Omega_{t}$ . [11] quoted after [19].

Many authors try to address the question of market efficiency with unconclusive results [6]. In this paper the author employs sample entropy method to verify the hypothesis.

### SAMPLE ENTROPY

Entropy is a way to measure complexity or dynamics of a given time series. Shannon entropy is classically defined as [5,4]:

$$H(X) = -\sum_{x_i \in \Theta} p(x_i) \log p(x_i) = -E[\log p(x_i)], (1)$$

where: *X* represents a random variable with a set of values  $\Theta$  and  $p(x_i)$  is a probability that *X* will be equal  $x_i$ . For a time series representing output of a stochastic process, joint entropy is calculated. A major disadvantage of this definition of entropy is that its value strongly depends on the length of the time series.

In 2000, Richman and Moorman proposed a new algorithm for the calculation of entropy, called sample entropy  $(S_E)$  [15], which is a function of the time series  $X=\{x_1, x_2, ..., x_N\}$ , template length *m* and tolerance *r*. In order to calculate  $S_E$ , the algorithm finds the first m-length sequence (template) of data points and then looks for matching pattern through the rest of the series. The pattern is considered as matching if the consequent data points are within a distance of r to the corresponding

points of the template. The number of matches is counted as  $n^m$ . Then the same procedure is performed for the m+1 - length sequence and the number of matches counted as  $n^{m+1}$ . The whole process is repeated until the end of the time series is reached. In this way  $S_F$  is defined as:

$$S_{E}(m,r,N) = \ln \frac{\sum_{i=1}^{N-m} n_{i}^{m}}{\sum_{i=1}^{N-m} n_{i}^{m+1}}.$$
(2)

The difference between  $n^m$  and  $n^{\prime m}$  is such that in  $n^{\prime m}$  self-matches are not counted. For an illustration of how the  $S_F$  is calculated, the reader is referred to reference [5].

 $S_E$  is precisely equal to the negative of the natural logarithm of the conditional probability that sequences close to each other for m consecutive data points will also be close to each other when one more point is added to each sequence [5]. When entropy is calculated in the previously stated method, it is less dependent on the length of the time series.

Sample entropy has been widely used in analysis of bioelectrical signals, mainly ECG and EEG [2,18,13,2]. Recently some attempts have been made to employ this technique in analysis of various markets (stocks and commodities) [1,14,8]. This paper aims to use Sample entropy to verify the Efficient Market Hypothesis.

#### DATA, METHODS AND TOOLS

The data that was used for the analysis was daily spot price of brent type crude oil for the years 1988 - 2011 (6091 points). The data is freely available from the Internet [20].

There is no consensus on how the prices of energy sources should be modeled [9]. In the presented study the author decided to take subsets of the original data points in two ways. The first method is to simply divide the data into periods of calendar years (approximately 255 points, depending of the year) and then calculate sample entropy for each period as described below. The second is to create subsets consisting of *z* data points continually for all points of the main dataset starting at point z until the end of the set according to the following expression:

$$Y_{i} = \{x_{i-z}, x_{i-z+1}, ..., x_{i}\},$$
(3)

in which  $Y_i$  is the subset calculated for the *i*-th point of input data. It is clear from looking at the equation that the smallest *i* for which the subset  $Y_i$  can be created equals z+1. In analogy to a moving average indicator used widely by technical traders,  $S_E$  calculated for subsets  $Y_i$ will be called "moving entropy" in this paper. The moving entropy was obtained for z=200.

Once the subsets are obtained, the data must be prepared for entropy calculation. As, according to the description presented in the previous subsection, the entropy algorithm looks for patterns and the price has various ranges, the value will be recalculated to obtain the day-to-day price difference  $Z_j$  using the equation (4):

$$Z_{i} = Y_{i} - Y_{i-1}.$$
 (4)

Then the data must be normalized so that the mean value of the subset is equal to 0 and standard deviation is 1. This can be illustrated by equation (5):

$$v_{si} = \frac{v_i - \mu(v)}{\sigma(v)},\tag{5}$$

where:

 $v_i$  is the price difference at point *i*,

 $v_{si}$  is the normalized value of v at point *i*,

 $\mu(v)$  is arithmetic mean of all points of *v*,

 $\sigma(v)$  is standard deviation of all points of v.

For each of the subsets  $S_E$  was calculated with typical parameters used widely: template length m=2 and tolerance r=0.15. The scripts used were based on the examples found on the Physionet website [10] and executed in the Octave programming environment [7].

In order to verify the Efficient Market Hypothesis, sets of random data points with normal distribution were generated. Its length depended on the subset length and for the yearly entropy comparison it consisted of 248 samples (lowest number of data points in the years analyzed) and for the moving entropy - 200. The number of test sets was equal to number of subsets of the original data according to each method: 24 for the 24 years used for yearly analysis and 5891 subsets for the moving entropy comparison. Additionally, to see some statistical properties (especially possibly maximum and minimum values) of  $S_r$  calculated for normal distribution 50 000 data sets of lengths respectively 248 and 200 samples were generated. Than, a statistical t-test was performed to verify whether the difference between entropies calculated for price data subsets and random sets is statistically significant.

#### RESULTS

Table 1 presents the  $S_E$  values for daily crude oil price in the years 1988-2011, table 2 summarizes its statistical properties and table 3 shows statistical properties of  $S_E$ calculated for 50000 samples calculated for data set of 248 points with normal distribution.

The p-value for statistical two-tailed t-test performed for 24  $S_E$  values obtained for yearly oil prices and 24 sets of 248 samples of random numbers with normal distribution is equal to 0.018 which proves that there is statistically significant difference between the groups.

Figure 1. presents daily brent price for the years 1988 - 2011 along with moving sample entropy. Because the first 200 points are needed to calculate the first value of the indicator, there first value is presented for point 201 on the chart.

The p-value for statistical two-tailed t-test performed for 5891 subsets of 200 points of daily oil price and 5891

Year	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
S <sub>E</sub>	1.990	2.451	1.604	1.545	2.329	2.475	2.533	2.356	2.569	2.327	2.345	2.456
Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
S <sub>E</sub>	2.322	2.350	2.547	2.448	2.425	2.467	2.483	2.465	2.374	2.451	2.405	2.321

Table 1. Sample Entropy values for crude oil prices for the years 1988–2011.

**Table 2.** Main statistical properties of SE calculated for crude oil prices for the years 1988 - 2011.

Maximum	Minimum	Arithmetic mean
2.569	1.545	2.335

 Table 3. Main statistical properties of SE calculated for

 50 000 sets of 248 normally distributed points.

Maximum	Minimum	Arithmetic mean
2.857	2.138	2.485

sets of 200 points of normally distributed random values is well below 0.0001.

# CONCLUSIONS

At the first look, the results of the analysis would support the Efficient Market Hypothesis: in most cases the values of the sample entropy calculated for lie within the range of SE values for random data sets. This would suggest that the price movements are random and it is not possible to forecast its future direction.

However if we take into consideration the results of the t-tests, it is clear that the behavior of the price is not random. The p-value for the yearly entropies for oil price and random data sets groups reflects the fact that the probability of the null hypothesis (i.e. that the two groups are not statistically different) is 0.018 which is very low. Traditionally, a level of 0.05 is considered as proving statistical significance. The value p-value for the moving sample entropy/sample entropy for random data sets is even lower.

The results show that the sample entropy value for crude oil price is lower than for randomly generated data with normal distribution, which means that the price change are more predictable than a purely random walk.

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Fig. 1. Daily brent price (black) and moving sample entropy indicator (grey) for years 1988-2011.

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#### ANALIZA ENTROPII ZMIENNOŚCI CEN ENERGII

S tr e s z c z e n i e. Artykuł przedstawia nowoczesną metodę analizy zmienności cen energii przy wykorzystaniu sample entropy, która to wielkość jest używana do określania złożoności oraz zawartości informacji w danym zbiorze danych (szeregu czasowym). Technika ta jest wykorzystana do weryfikacji hipotezy efektywności rynku. Wyniki wskazują, że pomimo że ruchy cen są niemalże losowe, istnieje statystycznie istotna różnica w porównaniu z czysto losowym ruchem cen.

Słowa kluczowe: cena energii, hipoteza efektywności rynku, sample entropy.

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# The use of production potential of vehicles on farms of different sizes

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S u m m a r y. The results of studies comparing the use of potential production capacity of means of transport in the context of farm size are presented. In the studied objects the level of annual use of the production potential is low, the lowest on average for trucks -4.53 %, and the highest for delivery vans -5.80 %. 67.11% of tractors are now fully depreciated. Among the most commonly used means of transport - box trailers, as much as 64.79% of trailers with an average load capacity (range 3-5 tons) are now fully depreciated.

Key words: transport, means of transport, tractors, trailers, cars, exploitation, production potential.

# INTRODUCTION

One of the main farm activities is transportation. Hence the correct, both qualitative and quantitative, selection of vehicles - which are one of the basic technical means - is directly reflected in the efficiency of transport works, but also in the expenditures incurred on a farm [2,6,1]. Reduction of expenses incurred for transport can be achieved by proper selection of the means and effective organisation of transport processes, and also by an optimum use of the resources [7,8,10]. The results of studies, presented by many authors, on the use and the associated level of effort clearly indicate that the volume of work and equipment, transport means and their use is usually characterized by considerable variability depending on the context of analysis [9,5]. Based on previous research, it can be concluded that the efficiency of means of transport varies considerably, and it results, among others, from the use of the potential and the ways in which such potential is used [2,3,11,13,12].

#### SCOPE AND PURPOSE OF THE STUDY

The effectiveness of management and the expenses for production depend not only on the technical resources -

including means of transport – but also on their use in the production process. Therefore, the objective of this study is to assess the use of the potential of means of transport, available on farms with various sizes of arable area. The subject of the study is multipurpose box-type means of transport available in selected farms in Małopolskie voivodship. 166 farms from Małopolskie voivodship were studied. The study included farms in the range of the secondary and vocational agricultural schools – children of the farm owners attend those schools and declare to take over the farms after graduating. It should therefore be presumed that the farms are developing entities. Due to large variations of the basic technology of agricultural production - agricultural areas of the surveyed farms were divided into three groups:

- A up to 10.00 ha 61 farms –36.75%;
- B 10.01 50.00 ha 83 farms 50.00%;
- C above 50.01 ha 22 farms 13.25%.

# **RESEARCH METHODS**

The research was conducted with the aid of a guided interview, and the objects of studies were selected deliberately – declaration to continue agricultural production at the same level or, which is quite frequent, increasing it. One of the basic questions of the interview concerned the available means of transport, their types and characteristics (load capacity, utilisation, year of manufacture and purchase). To evaluate the use of potential production capacity of means of transport, the ratio of production capacity utilisation was assumed after Tabor [Tabor 2008] as follows:

$$K_{wp} = \frac{W_{rz}}{n} \cdot 100, \qquad [\%]$$

where:

 $K_{wp}$  – the level of utilization of the production potential [%];

W<sub>rz</sub> – the actual utilization per annum [h];

n – resource – normative utilization of the resources during the lifetime [h];

Resource – the normative use during the lifetime according to the Swiss data, after Lorencowicz [5].

#### RESULTS

Table 1 characterises the farms under study. An average size of the studied farms was 26.24 ha of arable area, with considerable variability between the area groups A–6.46 to C – 97.14. A high level of permanent grassland is also remarkable, on average almost 27 %, as well as a considerable share of hired land – 38.83 % on average. These facts prove that the farm owners see their future in agricultural production. Farm size and livestock density, as the primary factors generating traffic volume are crucial for the equipment and structures of the owned means of transport. Another basic element is the distance of transport operations. The average distance for home transportation - 2.91 km - (2.04 Group A and 3.50 km Group B) is very high.

The considerable distance in the external transport, on average 15.25 km is characterized by low variability. Purchase of means of production and sales, in the case of commercial farms, shows no significant variations.

The number of tractors per 100 ha of arable land shows that the smallest farms are best equipped, this group can even be found over-invested in this respect. Average tractor power in all the area groups is very similar.

Similar differences are found in the means of transport as in the case of tractors. It has to be noted that the studied farms also owned special means, such as feed wagons, volume trailers and trailers for bales. Their average number per farm was 0.21, with the average load capacity 3.67 t. At the same time, each farm had dung spreaders, 0.94 pcs on average, with average load capacity 3.93 t. The index of tons of load capacity per 1 ha of arable land, with the average of 0.33 tons in the smallest farms, is almost 13 times higher than that of the largest farms. This may be perhaps due to the fact that the largest farms, because of the volume of purchasing of the production means and sales, hire companies which provide combined sales, purchase and transport.

Expenditures in transport depend not only on the equipment quantities, but mainly on the types of means.

Specification	unit	Farm size					
		average	Group A	Group B	Group C		
Arable area	ha	26,24	6,46	21,98	97,14		
% of AL share	%	73,09	62,69	60,24	86,01		
% of hired arable land	%	38,82	11,76	29,27	51,97		
Livestock	SD·100ha <sup>-1</sup> AL	69,18	61,22	79,05	49,77		
Installed power (tractors+trucks)	kW·1ha <sup>-1</sup> AL	9,45	8,04	14,24	18,03		
Internal transport distance	km	2,91	2,04	3,50	3,05		
External transport distance	km	15,25	15,56	14,24	18,03		
Tractors							
Number per 100 ha of arable land	pcs.	6,90	29,64	7,83	2,11		
Average tractor power	kW	50,01	49,59	51,63	45,93		
Means of transport*							
Number per 100 ha of arable land	pcs·100ha <sup>-1</sup> AL	10,78	32,5	10,24	2,57		
$\sum$ tons of load capacity per farm	t-farm-1	8,64	7,92	9,07	9,00		
Tons per 1 ha of arable land	t·1ha <sup>-1</sup> AL	0,33	1,29	0,41	0,10		
Average load capacity	t	3,88	3,78	4,03	3,60		
Share of means of transport in their load capacity per farm							
Trucks	%	4,64	3,41	3,83	10,60		
Delivery vehicles	%	6,26	5,65	5,67	10,02		
Box trailers	%	82,38	84,63	82,68	75,74		
Tractor cars	%	6,72	6,31	7,82	3,64		

**Table 1.** Description of the studied farms

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As the data presented clearly shows, the quality of transport fleet, expressed as a share of vehicles with total load capacity, increases with the area of farm. This is a very beneficial trend, since the transport needs and related expenditure in larger farms can be reduced by the use of more efficient means of transport.

In the studied objects (Table 2), the index of production potential use of tractors, with an average annual use of 527 h per tractor, is from 2.81 % in the medium-sized farms, to 10.85 % in the largest farms.

Comparing the number of years till full depreciation with the current age of tractors used after being fully depreciated, there are 68.11 % tractors in the studied population. In the group of box trailers, the average annual use of the production potential is 5.35 % and increases with the area of farms. In this group of vehicles, 42.15 % are fully depreciated – requiring replacemet. In spite of the low use of production potential in the group of trucks, all vehicles have not achieved the full depreciation level, and those are the youngest ones. In the group of delivery vans, only 23.21 % are fully depreciated.

The utilization of tractors depends on their basic technical parameter – engine power. For the analysis, division of tractors into so called operating groups has been adopted after Kuczewski. [Kuczewski J., Majewski Z. 1999].

Table	2.	Utilization	of production	potential
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Specification	Unit	Farm size					
		Average	Group A	Group B	Group C		
Tractors							
Operating hours p/a, field+ transport	h	527	281	479	1085		
The most beneficial resource	h	10000	10000	10000	10000		
Use of productivity	%	5,27	2,81	4,79	10,85		
No. of years to depreciate	years	19	36	21	9		
Current age	years	17	21	16	20		
% of means after resource	%	67,11	93,10	51,23	73,07		
	Box trailer	'S					
Operating hours p/a	h	294	161	288	479		
Resource	h	5500	5500	5500	5500		
Use of productivity	%	5,35	2,93	5,24	8,71		
No. of years to depreciate	years	19	34	19	9		
Current age	years	21	22	20	19		
% of means after resource	%	42,15	9,72	54,55	54,39		
Trucks							
Operating hours p/a	h	725	593	753	867		
Resource	h	16000	16000	16000	16000		
Use of productivity	%	4,53	3,71	4,71	5,42		
No. of years to depreciate	years	22	27	21	18		
Current age	years	12	15	10	10		
% of means after resource	%	0,00	0,00	0,00	0,00		
Delivery vehicles							
Operating hours p/a	h	545	536	549	570		
Resource	h	9400	9400	9400	9400		
Use of productivity	%	5,80	5,70	5,84	6,06		
No. of years to depreciate	years	17	18	17	17		
Current age	years	14	17	11	16		
% of means after resource	%	23,21	23,81	11,76	33,33		

Source: own studies.

Specification	Unit	Operating group of tractors			
		Light	Medium	Heavy	Very heavy
Operating hours p/a, field+ transport	h	400	446	583	1306
Resource	h	10000	10000	10000	10000
Use of productivity	%	4,00	4,46	5,83	13,06
No. of years to depreciate	years	25	22	17	8
Current age	years	24	18	12	5
% of means after resource	%	55,17	63,87	36,05	15,38

Table 3. Utilization of the production potential in context of power

Source: own studies.

Table 4. Utilization of the production potential of trailers in context of their load capacity

Specification	Trailer load capacity [t]				
	Olin	Up to 3,0	3 - 5	5 - 8	Above 8
Operating hours p/a	h	163	232	274	306
Resource	h	5000	5000	6000	6000
Use of productivity	%	3,26	4,64	4,57	5,10
No. of years to depreciate	years	31	22	22	20
Current age	years	19	23	18	7
% of means after resource	%	19,30	64,79	45,83	14,29

The results shown in Table 3 indicate a clear trend – the annual use of the potential of tractors significantly increases with the increase of their power. The most commonly used are the medium-sized universal tractors – 63.97 % are already fully depreciated.

The basic technical indicator of a transport vehicle, crucial for its applications and efficiency, is its load capacity. In general, it can be presumed that the use of the potential of the means of transport increases with the increase of load capacity.

This is a positive phenomenon, since vehicles with higher load capacity usually generate higher cost of use. The worst situation is in the group of medium trailers where, with the annual index of use 4.64 %, as much as 64.79 % trailers are already fully depreciated.

# CONCLUSIONS

Based on the results of the studies, it can be concluded that in the studied objects the level of annual use of their productivity is low, the lowest on average for trucks – 4.53 %, and the highest for delivery vans – 5.80 %. 67.11% of tractors are now fully depreciated, and for the trailers, the index is 42.15 %. Analyzing the use of tractors in context of their power, the medium-universal tractors were found to be the most commonly used ones. Among the most commonly used means of transport - box trailers, with the average annual use of the potential of Source: own studies.

5.35 %, as much as 64.79% of trailers with an average load capacity (range 3-5 tons) are now fully depreciated.

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#### WYKORZYSTANIE POTENCJAŁU PRODUKCYJNEGO POJAZDÓW NA FARMACH O RÓŻNYCH ROZMIARACH

Streszczenie. Artykuł prezentuje wyniki badań porównujących stosowanie potencjalnej zdolności produkcyjnej środków transportu w kontekście wielkości gospodarstw są prezentowane. W badanych obiektach poziom rocznego wykorzystania potencjału produkcyjnego jest niski, najniższy od średniej dla samochodów ciężarowych - 4,53%, a najwyższy dla samochodów dostawczych - 5,80%. 67,11% ciągników są to maszyny w pełni zamortyzowane. Wśród najczęściej wykorzystywanych środków transportu - przyczep skrzyniowych, 64,79% przyczep o średniej nośności (zakres 3-5 ton) jest w pełni zamortyzowane.

Słowa kluczowe: transport, środki transportu, ciągniki, przyczepy, samochody, eksploatacja, potencjał produkcyjny.

# Application of akaike information criterion for the detection of outliers

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Summary. For the detection of outliers (observations which are seemingly different from the others) the method of testing hypotheses is most often used. This approach, however, depends on the level of significance adopted by the investigator. Moreover, it can lead to an undesirable effect of "masking" the outliers. This paper presents an alternative method of outlier detection based on the Akaike information criterion. Statistical calculations and comparative analysis for the proposed method were conducted with commonly used statistical tests on the basis of the classical Grubbs experiment and the research into the combustion of biomass with plant composition. The advantages of the method and rationale for the selection of the appropriate statistical model were formulated in the form of conclusions.

Key words: outliers, data entropy, Akaike information criterion, Dixon test, Grubbs test.

# 1. INTRODUCTION

In the experiments carried out in the field of technical sciences, natural sciences and humanities we are often dealing with a sample, where the numerical values of some observations differ significantly from the others. The presence of such an observation in a sample (i.e. an outlier) may be due to various types of measurement errors, equipment failures, etc. In other words these observations should be regarded as undesirable, derived from a different population and ultimately excluded from statistical analysis.

However, outliers with apparently large or small values can be accepted by the probability distribution of the characteristic, which would mean that in the considered experiment we have a feature of less common value. So, it should be saved for further statistical analysis, thus increasing its efficiency.

For the detection and final evaluation (inclusion or exclusion from further analysis) of an outlying single observation the appropriate statistical test can be used, described by [24]. The problem with rejecting one outlying observation for the sample taken from a population with normal distribution was investigated by numerous researchers e.g. [8,9,10,12,16,18,25]. In a multivariate normal model rejecting outliers was considered e.g. by [8,13,17,20,21,23,24].

It should be noted that the detection of outliers with a test makes the statistical inference dependent on the level of test significance, which in practice may mean obtaining different conclusions for different levels of the test. Also, statistical conclusions drawn from the performed test often depend on the number of observations considered as outliers (masking outliers). This means that the same "suspicious" observations in one subset of measurements may be recognized as outliers, and in another may not.

The purpose of this paper is to present an alternative method for detecting outliers based on the general criterion of Akaike. This criterion, derived from information theory, was applied to select the best statistical model that describes (in terms of maximum entropy) real experiment data. The following discussion is based on the results of [1,2,21] allowing for the choice from the models describing real data of such a model that maximizes entropy by using the function:

$$4IC = -2\ln(W) + 2K,\tag{1}$$

where:

W-likelihood calculated for the parameter estimates, obtained by the method of maximum likelihood, K - number of parameters.

As suggested by Sakamoto, it would be best to choose the model for which AIC value is the lowest.

#### 2. THE MODEL OF OUTLIERS

Let us consider observation test n which, when rearranged according to increasing values, creates the set:

$$x_{(1)} \leq x_{(2)} \leq \cdots \leq x_{(n)}.$$

So  $x_{(k)}$  is the value of the k-th positional statistics  $X_{k,n}$ . In the rest of the paper we use the following notation:  $\psi(x; \mu, \sigma^2)$  is the density of a normal distribution with mean  $\mu$  and variance  $\sigma^2$ ,  $\Phi(x; \mu, \sigma^2)$  is the distribution function of this distribution, and  $f_r(x; \mu, \sigma^2)$  is the density of r-th positional statistics from the normal population, i.e.:

$$\psi(x,\mu,\sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left\{-\frac{(x-\mu)^2}{2\sigma^2}\right\},$$
 (2)

$$\Phi(x;\mu,\sigma^{2}) = \frac{1}{\sqrt{2\pi\sigma^{2}}} \int_{-\infty}^{x} \exp\left\{-\frac{(t-\mu)^{2}}{2\sigma^{2}}\right\} dt, \quad (3)$$

$$f_{r}(x;\mu,\sigma^{2}) = B(r,n-r+1)^{-1}\Phi(x;\mu,\sigma^{2}) \times \\ \times \left\{1 - \Phi(x;\mu,\sigma^{2})^{n-r}\right\} \psi(x;\mu,\sigma^{2}),$$
(4)

where:

$$B(p,q) = \int_{0}^{1} t^{p-1} (1-t)^{q-1} dt , \quad p > 0 , \quad q > 0 \quad (5)$$

denotes the function Beta [David 1979]. It is known that:

$$B(p,q) = \frac{\Gamma(p)\Gamma(q)}{\Gamma(p+q)} = \frac{(p-1)!(q-1)!}{(p+q-1)!}$$
(6)

for natural p and q.

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The model describing data with possible outliers after taking into account (2) - (6) can be represented by the density function:

$$h_{r}(x) = \begin{cases} \psi(x; \mu_{1}, \sigma^{2}) & 1 \le r \le n_{1} \\ f_{r-n_{1}, n-n_{1}-n_{2}}(x; \mu, \sigma^{2}) & r = n_{1}+1, \dots, n-n_{2}. \end{cases}$$
(7)  
$$\psi(x; \mu_{2}, \sigma^{2}) & r = n-n_{2}+1, \dots, n \end{cases}$$

The model described by (7) means that  $n_1$  of initial observations:  $x_{(1)}, \ldots, x_{(n_1)}$ ,  $n-n_1-n_2$  of the middle observations:  $x_{(n_1+1)}, \ldots, x_{(n-n_2)}$  and  $n_2$  of the final observations:  $x_{(n-n_2+1)}, \ldots, x_{(n)}$  are realizations of normal variables with the same variance  $\sigma^2$ , and the means, respectively,  $\mu_1, \mu, \mu_2$ . In this model, we consider the results  $x_{(1)}, \ldots, x_{(n_1)}$  and  $x_{(n-n_2+1)}, \ldots, x_{(n)}$  as "candidates" for outlying observations.

Likelihood function of the model (7) can be written as follows: n

$$L(x; n_1, n_2, \mu, \mu_1, \mu_2, \sigma^2) = \prod_{i=1}^{n} \psi(x_{(i)}, \mu_1, \sigma^2)$$
$$\times \prod_{i=n_1+1}^{n-n_2} f_{i-n_1, n-n_1-n_{23}}(x_{(i)}; \mu, \sigma^2) \times \prod_{i=n-n_2+1}^{n} \psi(x_{(i)}, \mu_2, \sigma_2)$$
(8)

From logarithms of functions (7) we get the relationship:

$$l_{1} = -\frac{1}{2} \left\{ n \ln 2\pi + n \ln \sigma^{2} + \frac{1}{\sigma^{2}} \sum_{i=1}^{n} (x_{(i)} - \mu^{i})^{2} \right\} - \sum_{i=n_{i}+1}^{n-n_{2}} \left[ \ln B(j,k-j+1) - (j-1) \ln \left\{ \Phi(x_{(i)}) - (k-j) \ln \left\{ 1 - \psi(x_{(i)}) \right\} \right] \right]$$
(9)

where:

$$j = i - n_1$$
,  $k = n - n_1 - n_2$  (10)

and

$$\mu^{i} = \begin{cases} \mu_{1}, & 1 \le i \le n_{1} \\ \mu, & n_{1} < i \le n - n_{2}. \\ \mu_{2}, & n - n_{2} < i \le n \end{cases}$$
(11)

By (8) - (11) the modified Akaike criterion (the minimum value (1)) takes the form:

$$AIC(i,j) = \begin{cases} -2l_1(x;i,j,\hat{\mu},\hat{\sigma}^2) + 2 \times 2 \quad (i=j=0) \\ -2l_1(x;i,j,\hat{\mu},\hat{\mu}_1,\hat{\sigma}^2) + 2 \times 3 \quad (i\neq 0,j=0) \\ -2l_1(x;i,j,\hat{\mu},\hat{\mu}_2,\hat{\sigma}^2) + 2 \times 3 \quad (i=0,j\neq 0) \\ -2l_1(x;i,j,\hat{\mu},\hat{\mu}_1,\hat{\mu}_2,\hat{\sigma}^2) + 2 \times 4 \quad (i\neq 0,j\neq 0) \end{cases},$$
(12)

where:  $\hat{\mu}, \hat{\mu}_1, \hat{\mu}_2, \hat{\sigma}^2$  denote parameter estimates obtained by the method of maximum likelihood.

# 3. STATISTICAL CALCULATIONS FOR CLASSICAL TESTS AND INFORMATION CRITERION

Below is a description of the most popular classical tests for detecting one or two outliers.

a) Tests for a single outlying observation

(i) 
$$T_1 = \frac{x - x_{(1)}}{s}, \quad T_n = \frac{x_{(n)} - \dot{x}}{s},$$
 (13)

where: s is the sample standard deviation.

b) Dixon tests

(ii) 
$$r_{ij}^{1} = \frac{x_{(i+1)} - x_{(1)}}{x_{(n-j)} - x_{(1)}}$$
  $r_{ij}^{n} = \frac{x_{(n)} - x_{(n-i)}}{x_{(n)} - x_{(j+1)}},$  (14)

where:

$$i = 1, j = 0 \quad for \ n \le 7, i = j = 1 \quad for \ n = 8,9,10, i = 2, j = 1 \quad for \ n = 11,12,13, i = j = 2 \quad for \ n \ge 14.$$
(15)

c) Grubbs tests:

(iii) 
$$L_1 = \frac{nS_1^2}{nS^2}$$
,  $L_n = \frac{nS_n^2}{nS^2}$ , (16)

where:

$$nS^{2} = \sum_{i=1}^{n} (x_{(i)} - \overline{x})^{2} ,$$
  

$$nS_{1}^{2} = \sum_{i=2}^{n} (x_{(i)} - \overline{x}_{1})^{2} \overline{x}_{1} = \frac{1}{n-1} \sum_{i=2}^{n} x_{(i)},$$
  

$$nS_{n}^{2} = \sum_{i=1}^{n-1} (x_{(i)} - \overline{x}_{n})^{2} , \quad \overline{x}_{n} = \frac{1}{n-1} \sum_{i=1}^{n-1} x_{(i)}.$$
 (17)

d) Tests for multiple outliers (single-sided case):

(iv) 
$$L_k = \frac{nS_k^2}{nS^2}$$
,  $L_{n-k} = \frac{nS_{n-k}^2}{nS^2}$ , (18)

where:

n-k

$$nS_{k}^{2} = \sum_{i=k+1}^{n} (x_{(i)} - \overline{x}_{k})^{2} , nS_{k}^{2} = \sum_{i=1}^{k} (x_{(i)} - \overline{x}_{n-k})^{2} ,$$
  
$$\overline{x}_{k} = \frac{1}{n-k} \sum_{i=k+1}^{n} x_{(i)} , \quad \overline{x}_{n-k} = \frac{1}{n-k} \sum_{i=1}^{n-k} x_{(i)}$$
(19)

e) Tests for multiple outliers (double-sided case):

(v) 
$$E_k = \frac{\sum_{i=1}^{n} (z_i - \overline{z}_k)^2}{\sum_{i=1}^{n} (z_i - \overline{x})^2},$$
 (20)

where:  $z_i$  is the value  $x_i$  of the i-th smallest distance from the mean  $\overline{x}$  and  $\overline{z}_k = \frac{1}{n-k} \sum_{i=1}^{n-k} z_i$ 

Critical values for these statistics for certain significance levels are given in [10,11].

Grubbs [1969] cites the following data on the percentage elongation at break of selected synthetic materials (after ordering):

# 2,02;2,22;3,04;3,23;3,59;3,73;3,94;4,05;4,11;4,13

In this case, you can only initially get interested in outlying observations to the left of the mean, because the very high readings indicate a remarkable plasticity of the material, which is a desired feature. Questionable results here are the two lowest values: 2.02, 2.22. We calculate the values of tests:

Below is the statistical calculation based on the figures from the experience performed by G. Maj in 2011. The experiment tested, among others, [May 2011] the percentage of ash in pellets made from 11 different plant materials, depending on the combustion temperature and moisture levels. Combustion of the tested biomass in the form of test pellets was performed using the muffle furnace Nabertherm L3/B180. 1-2 g test sample of solid fuel was placed in the oven and heated to the temperature of 600°C or 815°C. The ash content in the test sample of solid fuel was calculated using the following formula:

$$\begin{cases} T_{1} = \frac{3,406 - 2,02}{0,7711} = 1,7975 \\ r_{11}^{1} = \frac{2,22 - 2,02}{4,11 - 2,02} = 0,0975 \\ L_{1} = \frac{3,217}{5,351} = 0,6011 \\ L_{2} = \frac{1,197}{5,351} = 0,224 \end{cases}$$
$$A^{a} = \frac{m_{3} - m_{1}}{m_{2} - m_{1}} \bullet 100 \tag{21}$$

where:

A<sup>a</sup>- ash content of the test sample [%],

m<sub>1</sub>- ignited cell mass [g],

m<sub>2</sub>- cell mass with the weighed solid fuel [g],

 $m_3^{-}$  cell mass with ash [g].

One series of measurements in the context of our discussion seems to be particularly interesting. The giant *Miscanthus* combusted at 815°C rendered the following results:

## 3,4;3,42;3,45;3,67;3,71;25,93.

The theory presented in Part 2 allows calculation of the Akaike information criterion for various configurations of outliers. The results of calculations are presented in Table 4.1, while the values of classical tests after the calculations are as follows:

$$T_{6} = \frac{25,93 - 7,625}{8,3481} = 2,2358,$$
  
$$r_{10}^{6} = \frac{25,93 - 3,71}{25,93 - 3,41} = 0,9867,$$
  
$$L = \frac{0,0849}{418,14} = 0,002.$$

 Table 4.1. Values of Akaike information criterion for the ash content in giant *Miscanthus*

	High outliers						
		None	25,39	25,39 4,25			
~	None	32,6507	32,0385 *	43,4342			
utlier	3,41	38,4383	37,8094	44,4609			
Low o	3,41 3,42	41,1633	40,9162	46,7224			

### 4. SUMMARY AND CONCLUSIONS

The presented modified Akaike information criterion allows for the choice of the correct statistical model in the set of models describing a particular experiment and takes into account the maximum value of entropy. At the same time it is independent from the selected different levels of significance of statistical tests used to verify the hypotheses formulated within the study. Simultaneously, it is an analytical indication concerning the exclusion of the optimal number of outliers in the sample, while maintaining a hypothetical probability distribution of the tested characteristic. Unambiguous indication by the criterion of the outliers which need to be removed naturally eliminates the potential for masking effect of outliers in the sample.

Conclusion 1. The classic experiment of Grubbs discussed by many authors is a typical example of the ambiguity of statistical inference based on the classical tests. None of these tests recognizes the outlying of the lowest value (the lowest single observation) in the sample. The resulting test values do not exceed the predicted critical thresholds because  $T_1 < 2,18$ ;  $r_{11}^1 < 0,477$ ;  $L_1 \ge 0,418$ , while the calculated value  $L_2 = 0,224 < 0,2305$  at the significance level  $\alpha = 0,05$  detects the outlying of the two lowest observations, while for higher values  $\alpha$  still does not detect outlying.

The above-mentioned problems are not noticed in the case of the modified Akaike criterion, since the lowest value of the function (1.1) at 16.041 obtained for the two low outliers clearly suggests the rejection of the two lowest observations.

*Conclusion 2.* The calculated values of the criterion presented in Table 4.1 clearly indicate the correct model configurations (single outlier value to the right of the mean), because the maximum observation value 25.39 (shown in Table 4.1) corresponds to the minimum value of the function (1.1). This conclusion, in this case, is consistent with the conclusions of the classical tests, since at the level of significance  $\alpha = 0.05$  we obtain:

 $T_6 = 2,2358 > 1,996;$   $r_{10}^6 = 0,9867 > 0,56;$   $L_1 = 0,002 < 0,2032$ 

which means that the values of all the classical tests are in the critical area.

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#### ZASTOSOWANIE KRYTERIUM INFORMACYJNEGO AKAIKE DO WYKRYWANIA OBSERWACJI ODSTAJACYCH

S tr e sz c z e n i e. Do wykrywania obserwacji odstających (pozornie odbiegających od pozostałych) najczęściej stosuje się metody testowania hipotez. Podejście takie zależy jednak od przyjętego przez badacza poziomu istotności. Ponadto może ono prowadzić do niepożądanego efektu "maskowania" ostających obserwacji. W niniejszej pracy przedstawiono alternatywną metodę wykrywania odstających obserwacji bazującą na kryterium informacyjnym Akaike. Kalkulacje statystyczne oraz analizę porównawczą, proponowanej metody z powszechnie stosowanymi testami statystycznymi, przeprowadzono na podstawie klasycznego eksperymentu Grubbsa oraz badań dotyczących spalania biomasy o składzie roślinnym. Zalety metody oraz uzasadnienie wyboru odpowiedniego modelu statystycznego sformułowano w postaci wniosków końcowych. Słowa kluczowe: obserwacje odstające, entropia danych, kryterium informacyjne Akaike, test Dixona, test Grubbsa.

# Jerusalem artichoke (Helianthus Tuberosus L.) as renewable energy raw material

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Summary. Jerusalem artichoke was previously used as raw material, food, pharmaceutical and fodder. Its yield potential and low requirements meant that it could be of interest in the energy sector. Aboveground parts turned out to be a good raw material for production of fuel pellets. Studies have shown high energy value of dry stalks of Jerusalem artichoke two varieties: Albik and Rubik. The parameters characterizing the aboveground plant parts were similar to other types of biomass. There were no significant differences in the chemical composition or energy parameters of the tested cultivars. Sulfur and chlorine content exceeds the standards that apply to the pellet in some European Union countries, which indicates a less useful raw material for production of pellets. Jerusalem artichoke ash has a high content of alkali oxides and low melting temperatures, which indicates the risk of its deposition on heating devices. Accordingly, it is proposed to mix Jerusalem artichoke plant biomass with other raw materials.

Key words: Jerusalem artichoke, biomass, heating value, ash content.

#### **INTRODUCTION**

High potential yield and wide possibilities of using Jerusalem artichoke (Helianthus tuberosus L.) have caused an increase of interest in this species. There are many uses of this plant, but in Poland it is used mainly as a vegetable for food. Especially tubers with white skin and regular shape are widely used for culinary purposes on chips, salads and as cooked and fried foods. Tubers are also a good raw material for alcohol production (including energy sources) and fructose syrups. They can be used for animal feed, without evaporation, as is the case with feed potatoes. The tubers contain inulin polysaccharide, particularly valuable in the diet of diabetics. The juice of the tubers and flower infusions are used to treat gastrointestinal diseases. Jerusalem artichoke stems and leaves are fed to livestock animals, they are also suitable for silage, drought or pellets for animals.

Chaff from the raw stems is a good substrate for the production of edible fungi, including oyster [2]. Due to the rich set of polysaccharides, proteins, organic acids, vitamins and other compounds, bulbs and flowering tops of young shoots are also a raw herb.

Jerusalem artichoke, as a species with great ability to bind solar energy and processing of the biological mass, can be used as energy plant for direct combustion, cofiring with coal and the production of biogas [5, 6, 16, 14, 20]. Another form of use of this species is the reclamation of land devastated by the industry and utilities [2]. Jerusalem artichoke is a species with very high production potential. On fertile soils, with plenty of water, fresh biomass yields can reach up to 200 Mg per ha, and yield the same tubers to 90 Mg×ha<sup>-1</sup>× [1, 15]. In Polish conditions, average dry matter yield of aboveground parts ranges from 10 to 16 Mg×ha<sup>-1</sup>, and of tubers 12-36 Mg×ha<sup>-1</sup>.

#### MATERIALS AND METHODS

Aboveground parts of two varieties of Jerusalem artichoke: Albik and Rubik were obtained at the Experimental Station of the University of Life Sciences in Lublin, located in Zamość on brown soil, belonging to quality class II, good wheat complex. Biomass in the form of residual stems and leaves (most leaves had fallen under the influence of wind and precipitation) were collected after drying in the winter of 2005 and 2006. Random samples in bulk were analyzed for the elemental content, energy and heat of combustion in the Power Research and Testing Company "Energopomiar" in Gliwice. Measurement of moisture content, ash content and volatile matter were made by gravimetric method. To determine the heat of combustion of biomass, calorimetric method was used. Based on this, the calorific value was calculated, according to the following formula:

$$Q_i = Q_s - L (9H_t + W_a)$$
 (1)

where:

 $Q_i$  - net calorific value  $Q_s$  - gross calorific value L - heat of vaporization (2 257 kJ·kg<sup>-1</sup>)  $H_t$  - hydrogen content  $W_a$  - moisture Study of carbon, hydrogen and sulfur was performed

by infrared absorption, nitrogen - by katharometric method, and chlorine - by titration. Biomass analysis was performed for analytical, dry and ash-free dry states.

Ash was obtained at 600 °C, the elemental composition was analyzed with plasma spectrometer ICP OES. The contents of individual components were given for the dry state. Characteristic melting temperature of ash as determined (in half-reduced atmosphere): as well as the temperature of sintering, softening, melting and pour. Based on the analysis results, the  $c_m$  coefficient was calculated, which characterizes ash susceptibility to form deposits, according to the following formula [18]:

$$c_{\rm m} = \frac{Fe_2O_3 + CaO + MgO + Na_2O + K_2O + P_2O_5}{SiO_2 + Al_2O_3 + TiO_2}$$
(2)

#### RESULTS

Analytical samples were characterized by a similar moisture level 9,6-9,7% (Tab. 1). This moisture, known

as air-dried, stored in biomass is characterized by a room devoted to combustion or pre-processed to form granules: briquettes or pellets. Perennial plants, where the aboveground parts dry up after the end of the growing season, have a high dry matter content without drying, which also results in low moisture of samples. This feature also applies to Jerusalem artichoke and is one of its advantages.

The ash content was slightly higher in the stems of the variety Rubik, which was 5.1% in the state analysis and 5.6% in absolute dry state and in the aboveground parts of the variety Albik, which was respectively 4.9 and 5.4%. The content of combustible substances of both cultivars was very similar and amounted to an average of 85.4% in the analytical condition and 94.5% in the dry state. Also content of volatile matter in biomass was not dependent on the varieties of Jerusalem artichoke.

The heat of combustion of biomass of the examined varieties of Jerusalem artichoke obtained analytically varied within narrow limits 15.64-15.81 MJ×kg<sup>-1</sup>, while in the dry state 17.31-17.49 MJ×kg<sup>-1</sup>, while the calorific value, respectively 14.32-14.49 MJ×kg<sup>-1</sup> and 16.10-16.30 MJ×kg<sup>-1</sup> (Tab. 1). The study revealed that the variety Albik was characterized by less favorable energy parameters, which results from its chemical composition. The carbon content, the desired element in any energy raw materials, was present in the biomass at 41.72% in Albik and 46.16% in the dry state, while in the stems of the variety Rubik, respectively, at 43.27% and 47.90%. At the same time higher oxygen content was reported in the biomass of Albik variety.

Biomass of selected varieties of Jerusalem artichoke was also examined in terms of sulfur content and chlorine

**Table 1.** Energetic parameters of two cultivars of Jerusalem artichoke

			Condition					
Parameter	Symbol	Unit	analytical		dry		dry and ash-free	
			Albik	Rubik	Albik	Rubik	Albik	Rubik
Analytical moisture	W <sub>a</sub>	%	9,6	9,7	-	-	-	-
Ash	А	%	4,9	5,1	5,4	5,6	-	-
Burnt matter	-	%	85,5	85,3	94,6	94,4	-	-
Volatile matter	V	%	67,2	66,9	74,4	74,1	78,6	78,5
	Q <sub>s</sub>	kcal·kg <sup>-1</sup>	3 736	3 775	4 134	4 179	4 371	4 427
Gross calornic value		MJ·kg <sup>-1</sup>	15,64	15,81	17,31	17,49	18,30	18,53
Not colorific volue		kcal·kg <sup>-1</sup>	3 419	3 460	3 846	3 892	4 066	4 123
Net calornic value	Q <sub>i</sub>	MJ·kg <sup>-1</sup>	14,32	14,49	16,10	16,30	17,02	17,26
Carbon	C <sub>t</sub>	%	41,72	43,27	46,16	47,90	48,81	50,74
Hydrogen	H	%	4,97	4,94	5,50	5,47	5,81	5,79
Oxygen	0	%	38,69	36,92	42,81	40,87	45,26	43,29
Nitrogen	N	%	0,08	0,10	0,09	0,11	0,09	0,12
Total sulphur	S <sub>t</sub>	%	0,02	0,05	0,02	0,06	0,02	0,06
Chlorine	Cl	%	0,190	0,240	0,210	0,266	-	-

Source: own research

- the elements responsible for the corrosion of heating appliances. Participation of sulfur was 2.5-fold higher in the biomass of Rubik variety and 3-fold higher for dry and ash-free dry mass. The difference was less chlorine content, although the stems of the variety Rubik's contents were higher (Tab. 1).

 Table 2. Composition of Jerusalem artichoke biomass ash

 [%]

Comment	Course 1	Cultivar		
Component	Symbol	Albik	Rubik	
Silikon dioxide	SiO <sub>2</sub>	7.83	6.80	
Iron	Fe <sub>2</sub> O <sub>3</sub>	0.50	0.51	
Aluminium	Al. <sub>2</sub> O <sub>3</sub>	0.46	0.46	
Manganese	Mn <sub>3</sub> O <sub>4</sub>	0.04	0.05	
Titanium	TiO <sub>2</sub>	0.02	0.02	
Calcium	CaO	19.7	18.8	
Magnesium	MgO	2.40	1.06	
Sulphur	SO3	1.83	1.85	
Phosphorus	P <sub>2</sub> O <sub>5</sub>	5.35	3.69	
Sodium	Na <sub>2</sub> O	0.45	0.54	
Potassium	K <sub>2</sub> O	33.7	35.8	
Barium	BaO	0.03	0.04	
Strontium	SrO	0.07	0.09	
Chlorides	Cl	3.88	4.74	
Carbonates	CO <sub>2</sub>	22.8	24.6	
c <sub>m</sub> coefficient	c <sub>m</sub>	7.47	8.30	

Source: own research

Small differences were found out in the elemental composition of Jerusalem artichoke cultivars of ash (Tab. 2), while in the biomass the significant characteristic was the alkali oxide content, responsible for the reduced melting temperature of ash. There was particularly high CaO and  $K_2O$  content in ash (18.8 and 19.7% for CaO, and 33.7 and 35.8%  $K_2O$ ). The ash of the variety Albik also showed large amount of  $P_2O_5$  (5.35%). The sum of alkali oxides in the ashes of both varieties is large and shows the danger of a strong build up of deposits on the heaters during the combustion of biomass. Greater presence of chlorides in the ash of the variety Albik contained 3.88% chloride (Tab. 2).

The ash of Jerusalem artichoke was characterized by relatively low melting point (960-965°C), which makes it strongly adhere to the heating surface of boilers, heat exchange disturbing (Tab. 3). Ash flow temperature of the variety Albik was higher in comparison with the ash of the variety Rubik.

**Table 3.** Characteristic fusibility temperature of Jerusalem artichoke ash [°C]

Temperature	Symbol .	Cultivar		
[°C]	Symbol	Albik	Rubik	
Sintering	t <sub>s</sub>	620	620	
Softening	t <sub>A</sub>	685	690	
Melting	t <sub>B</sub>	965	960	
Pour	t <sub>c</sub>	1260	1120	

Source: own research

# DISCUSSION

The most important parameters of thermophysical fuels are: calorific value and heat of combustion. These parameters depend mainly on the chemical composition and humidity of the material. The calorific value of dry straw is contained in a relatively narrow range and depends primarily on the type of plant: from 14 to 15 MJ×kg<sup>-1</sup>. For comparison, the calorific value of coal varies from 18.8 to 29.3 MJ×kg<sup>-1</sup> [4]. In studies of [16] the average calorific value of Jerusalem artichoke was 15.6 MJ×kg<sup>-1</sup>, but that varies from 14.8 to 16.4 MJ×kg<sup>-1</sup>. [10] described the heat of combustion of biomass with moisture content 20% to about 15 MJ×kg<sup>-1</sup> biomass, while [7] obtained the value of 14.9 MJ×kg<sup>-1</sup> in working conditions (17.6% humidity), while in the dry state -18.0MJ×kg<sup>-1</sup>. The calorific value of Jerusalem artichoke with the humidity of 15%, determined by [14], amounted to15.9 MJ×kg<sup>-1</sup>. The calorific value of Jerusalem artichoke as defined in our study can analytically oscillate around14.4 MJ×kg<sup>-1</sup>. The heat of combustion ranged at 15.64-17.49 MJ×kg<sup>-1</sup> depending on the moisture content of the raw material and it showed typical values for many types of biomass [8, 18]. Moilanen [11] reviewed the literature on the chemical composition and energy parameters of biomass from agriculture and forestry. As is clear from the data presented by him, the minimum calorific value was 16.75 MJ×kg<sup>-1</sup>, and the maximum specified in the dry state was 19.70 MJ×kg<sup>-1</sup> (heat of combustion, respectively 18.06 and 20.95 MJ×kg<sup>-1</sup>), while the minimum values were found for cane biomass, and the maximum ones for the bark of pine trees. [12] compare the calorific value of straw (wheat, barley, rapeseed, corn), granules (pellets, wood briquettes and straw), wood chips and oats. The calorific value of all the energy raw materials was contained in the range 14-18 MJ×kg<sup>-1</sup>, with the highest energy value characterized by the pellet. Comparison of the results of the authors' own research and presented in database containing information about the energy performance of biomass and some waste [Phyllis] indicates that the composition and energy value of Jerusalem artichoke is comparable with the one presented in the literature.

The combustion of clean biomass produces small amounts of ash and its contents in biomass is 0.5-12.5% [12]. Although ash from the combustion of biomass can

be used for fertilizing, considering the possibility of using plant materials in co-firing, excessive ash content may be unfavorable feature. The ash content in coal, according to research of [18] is 22.2%, is 0.3% in pine, 0.8% in beech, 2.2% in willow biomass. Reported [4] that the ash content in coal is 12%, 3-4% in cereal straw, and in wood is even smaller and ranges from 0.6 to 1.5%. Niedziółka and Zuchniarz [12] have reported that during the combustion of clean biomass, a small amount of ash is produced, estimated at 0.5-12.5%, while its larger share of the pollution provides the raw material. Wilk [21] defines the ash content in the biomass of wood on 0.3-7.4%, while in the straw of cereals on 4.3-10.4%. According to the author there is a weak negative correlation between ash content and energy value of raw material, and it calculated the correlation coefficient at 0.3093, which means that with increasing ash content in the biomass a decline in the value of heat of combustion follows. In light of the quoted results it can be stated that the ash content in the biomass of two cultivars of Jerusalem artichoke, analyzed and presented in our study, did not differ from the average values obtained for other plant materials. Biomass of Rubik and Albik varieties were characterized by the participation of ash at the level of 4.9-5.1% DM, but in the light of standards for pellets [8] they did not meet their requirements.

Jerusalem artichoke biomass also exceeded Western European standards for wood pellets in terms of chlorine content. Wilk [21] states that the maximum chlorine content found in the straw of different plants studied in the laboratory of the Institute for Chemical Processing of Coal stood at 1.023%, while in biomass wood at 0.039%. Ściążko et al. [18] have emphasized that the high content of chlorine can lead to increased corrosion and corrosive sludge accumulation in the boiler during the direct combustion of biomass. Total sulfur content in the biomass of Jerusalem artichoke was measured in hundredths of a percent (0.02-0.05%), while [3] has reported that in the straw of different species of agricultural plants the sulfur content is 0.1-0.4%.

The high carbon content of energy raw materials is very desirable, because correlative relationship between the content of this element and the calorific value of biomass is positive. In studies of [21] coefficient of determination  $R^2$  was 0.9976. The share of carbon in dry weight Jerusalem artichoke ranged from 46.16 to 47.90%, while in the straw it was 42-43%, and in coal 59% [4].

Wasilewski [19] compares the composition of the ash from combustion of coal and wood chips from willow and beech. The content of alkali oxides in the ash from coal is low and amounts to: 2.66% CaO, 2.98% K<sub>2</sub>O, 0.89% P<sub>2</sub>O<sub>5</sub>. In the ash from willow it is, respectively: 44.5, 8.51 and 5.9%, while in the beech chips these values are as follows: 29.6, 10.27 and 2.68%. The percentage of SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub>, thus limiting the adverse properties of oxide deposition of ash on heating devices, in the ash from coal its total is 79.46%, while 22.49% from willow and 34.1% from beech chips. Also [18] have indicated a much higher content of acidic compounds in the ash resulting from burning coal (the sum of  $SiO_2$  and  $Al_2O_3$  was 79.7%) compared to the ashes of wood (16.9%), straw (50.3%), sediment sludge (31.4%) and bone meal (5.96%).

According to research conducted by the Institute for Chemical Processing of Coal in Zabrze [19], the melting temperature of coal ash amounted to (°C):  $t_s$  920, 1230  $t_A$ ,  $t_B t_C$  1400 and 1420°C For ash willow chips these temperatures were, respectively: 830, 1520, 1530 and 1540°C, for spruce sawdust: 1090, 1190, 1220, 1290°C, for two samples of cereal straw: 800÷810, 860÷900, 1140÷1150 1220÷1280°C. Ściążko et al. [18] have mentioned that the characteristic melting temperature of both fly ash from coal, biomass as well as the one designated on a laboratory scale often give insufficient information on potential risk slagging of heating surfaces, due to different design solutions for boilers, prolonged exposure to exhaust, the combustion process changes, etc. .

### CONCLUSIONS

The observed growing demand for biomass energy has caused considerations of the possibility of the energy use of plants grown for food and feed. Particularly desirable features of energy crops are: a high potential yield, resistance to environmental conditions and durability. These features are present in Jerusalem artichoke. The study shows that the above-ground parts obtained after drying are characterized by the energy parameters which are not inconsistent with other types of biomass. Varieties Albik and Rubik have similar chemical composition and energy parameters. The stems of both varieties have a relatively high content of chlorine and sulfur, and therefore their mixing is proposed with other types of biomass for the production of granules (pellets), which will be important in order to meet quality parameters. Negative feature is the Jerusalem artichoke biomass chemical composition of ash and its low melting temperature. These parameters indicate the risk of deposition of the heating devices and thus reducing the efficiency of boilers.

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#### SŁONECZNIK BULWIASTY (*HELIANTHUS TUBEROSUS* L.) JAKO ODNAWIALNY SUROWIEC ENERGETYCZNY

Streszczenie. Słonecznik bulwiasty znajdował dotychczas wykorzystanie jako surowiec spożywczy, farmaceutyczny i paszowy. Jego duży potencjał plonowania i małe wymagania sprawiły, że znalazł się w kręgu zainteresowania energetyki. Części nadziemne okazują się być dobrym surowcem do produkcji granulatów opałowych. Badania wykazały wysoką wartość energetyczną suchych łodyg słonecznika bulwiastego dwu odmian: Albik i Rubik. Parametry charakteryzujące nadziemne części roślin były zbliżone do innych rodzajów biomasy. Nie stwierdzono znaczących różnic w składzie chemicznym badź parametrach energetycznych badanych odmian. Zawartość siarki i chloru przekracza normy, jakie obowiązują dla peletów w niektórych krajach Unii Europejskiej, co wskazuje na mniejszą przydatność surowca do produkcji granulatów. Popiół topinamburu charakteryzuje się wysoką zawartością tlenków alkalicznych i niskimi temperaturami topliwości, co świadczy o ryzyku jego odkładania się na urządzeniach grzewczych. W związku z powyższym proponuje się mieszanie biomasy topinamburu z innymi surowcami roślinnymi.

Słowa kluczowe: słonecznik bulwiasty, biomasa, wartość opałowa, zawartość popiołu.

# Directions of the reclamation and development of wasteland

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S u m m a r y. In the publication, the issues associated with land use and reclamation were presented. Causes of land degradation resulting in the creation of wasteland and directions of its reclamation were characterized. When choosing the direction of restoration, the development plan objectives have been taken into account, as well as the local needs and protection of the environment. The forest or agricultural directions are the commonest and the complete or partial reconstruction of the soil profile is the basis of reclamation.

In the last decades vast agricultural areas have been excluded from use. They were allocated mainly for housing estates, industrial areas, roads and communications paths, mining areas or water reservoir sites. Simultaneously, thanks to reclamation and the following development, a great deal of the downgraded part has been restored for agricultural use.

Key words: reclamation, land use, wasteland, decline, devastation, agriculture, soil, land.

#### INTRODUCTION

Life of the man is inseparable from using the environment, which also involves exploitation of the needed raw materials. Such activity can affect positively or negatively the environment, and in many cases it leaves a permanent track. The destroyed or vandalized surface of the earth requires a thought-over and effective reclamation and the following development. One of the legal documents concerned is the Reclamation Act on the Protection of Agricultural and Forest Areas, which resolves the principles of protection of agricultural and forest lands as well as the reclamation and improvement of the utility of ground.

The process of reclamation consists in the restoration of the utility of ground which has been downgraded or vandalized as a result of human activity or natural disasters, through performing technical, biological or agrotechnical treatment. We rank the ground degraded by the industry and mining, landfill sites, slag heaps among areas requiring reclamation and the like [10,11,18]. Reclaimed ground should be subjected to rational development consisting in the realization of the sequence of treatments which will enable to use this ground to agricultural, forest, or other purposes.

The reclamation and development are interrelated. The direction of reclamation has a considerable influence on the direction of development and depends on: demographic conditions, the structure of using the surrounding ground, costs of individual tasks, land development plan on which the reclaimed area lies and needs of changes in the structure of using the area [13].

In order to expand cities, build motorways and new factories, new areas are needed. Therefore, the change is inevitable from using agricultural lands to other functional purposes. According to the statistical yearbook in Poland in the years 2000 – 2009, 23 thousand ha of agricultural lands were turned off to nonagricultural destinations, including 15 thousand ha of farmland [2]. In order to stop this rush one should reclassify areas in the well-conceived way and, if possible, conduct the rehabilitation in agricultural direction.

# PROTECTION OF LAND

The protection of ground consists in reducing activities affecting the environment and downgrading or vandalizing the areas in question.

Agricultural and forest areas constitute a crucial element in the functioning of environment, therefore their appropriate protection is important. In the light of the act from 3 February, 1995 on the protection of agricultural and forest areas, the protection of agricultural areas consists in:

 limiting their allocation to non-agricultural or nonforest units,

- preventing the degradation processes and devastation of agricultural land as well as damage in agricultural production occurring as a result of non-agricultural activities and of movements of the earth masses,
- reclaiming and developing land towards agricultural purposes,
- keeping peat bogs and small ponds,
- limiting changes of the natural shape of the earth areas.
   Similarly, the protection of forest areas consists in:
- limiting their allocation to non-forest or non-agricultural units,
- preventing degradation processes and devastation of forest lands as well as the damage in tree stands and forest production resulting from non-forest activity and movements of the earth masses,
- restoring the utility of ground which lost the character of forest land as a result of non-forest activity,
- improving their utility as well as preventing or lowering their productivity,
- minimizing the changes of natural forming of the earth area.

The level of soil protection is dependent on two factors, the origins and class. The highest classes and organic soils deserve top protection levels [3].

# THE DECLINE AND DEVASTATION OF THE SOIL ENVIRONMENT

The industrialization and urbanization are the main causes of soil degradation causing the increase of wasteland. The destructive character of this devastation is obvious, the effects are most often irreparable, and the adverse influence is unquestioned. The decline of soil is caused by many factors, and the most important are: the building development and changes in using ground, mining exploitation of raw materials, waste disposal, industrial and automotive environmental pollution, use of chemicals in farming and forest, water and wind erosion, inappropriate land reclamation [17].

With its big interference in the environment, mining is the branch of industry which is most often matched up. It results from the specificity of the mining industry both underground, above the ground and to a large degree opencast. It is an undeniable fact that in Poland over 60% of all wasteland is the effect of activity of coal mining and the mining of raw materials [1]. The area of land occupied by the mining engineering is decreasing and in 2008 it was over 36 thousand [2] ha. Until recently, they still left the degraded areas to themselves without any corrective actions, hoping that the nature alone would restore a particular area. It contributed to the creation of the opinion that mining was highly harmful to the environment. At present, restoration works are being conducted not only after the completed use but also while the use is lasting.

Nevertheless, wasteland is coming into existence for natural reasons and it includes; bogs, sand dunes, areas with disadvantageous land features on which conditions for inhabiting are insufficient. Such wasteland, incurred for natural reasons, should be protected, since in spite of the lack of utility it usually has a considerable natural value. In the years 2000 - 2010 wasteland constituted 1.6% of the area of the country [2].

Every owner of land, including farmlands and ground reclaimed to agricultural destinations, is obliged to the counteraction of soil decline. If a suspicion exists about the possibility of the appearance of erosion or of mass movements the afforestation rate can be ordered to the owner of the ground by way of a decision requiring the afforesting, planting bushes on the ground or arranging permanent grassland on it. Also, the duty of keeping the technical efficiency of devices in the state preventing erosion and of devices of detailed land reclamation lies with the landholder on which the devices are staying.

The basic forms of soil degradation include: erosion, acidity, making barren, alkalization, salinity, breach of balance between nutrients, environmental pollution of soil with toxic elements.

Erosion of soil is the process of soil cover decay which in a significant way influences the sculpture of the earth's crust. It can be triggered by water, wind or, in special cases, gravity. For its straining depends on the terrain, properties of topcoat of the lithosphere, climatic conditions, flora and the way of using ground [1]. The dense flora constitutes the cover of soil, influences its properties, increases the water retention, shapes the local microclimate and influences the accumulation of nutrients. The liquidation of flora in order to increase the cultivated area increases the erosion processes to a considerable degree. It is caused by the long-lasting or periodic denudation of soil and performance of treatments aerating the soil. The sandiest soils are exposed to erosion and weakly clayed. They are characterized by great permeability and low content of functional constituents. Agricultural use of sandy ground causes a sequence of disadvantageous changes such as: increased outflow of rain waters, scouring fertilizer elements, which in consequence results in fertility decrease. Finally, the lowered profitability of cultivation causes cease of the agricultural use and appearance of wasteland. In Poland, 27.6% of the cultivated soil is potentially threatened with wind erosion, including 17.3 in the weak degree, 9.3% in the average degree and 1% in the strong degree. 27.5% of agricultural and forest areas are endangered with surface water erosion, and17.5% with ravine erosion [2].

Acidification of soil is an enormous problem all over the country. It is caused by air pollution, applying mineral fertilizers for a long stretch of time, activity of bacteria, decomposition of humus and storage of sour and acidic waste in landfills. Under natural conditions, soils are characterized by high acidity caused by some sedimentary rocks [12]. As a result of soil acidification a sequence of disadvantageous changes occurs: nutrients are scoured, the concentration of toxic metals and other adverse factors in the soil grows, roots of plants are damaged. The effective but also long-term method of neutralization of acid soils is liming. In order to neutralize the compact soil to the reaction being neutral for a majority of plants, even several dozen years are needed. According to the statistical yearbook in the year 2009 the area of soil requiring liming in different degrees reached 72%. These results were received after examining 3635 thousand ha of the area.

Making the soil barren consists in the drop of nutrients. It is most often caused be applying the monoculture i.e. the cultivation of one kind of soil plants with about the same requirements in the same area for a few years. As a result, the reduction in content of nutrients which can assimilate in the soil causes the dwarfing of plants. In the organic cultivation, fertilizing with manure and mineral fertilizers is the best-known way of soil enrichment. At present, a research on fly ashes applicability to this purpose is being conducted [16].

Another adverse factor is upsetting the balance between nutrients. With every collected crop there comes a whole range of nutrients, especially microelements. In order to supplement them, mineral fertilizers which in contrast with natural fertilizers do not have all the essential microelements are more and more often applied. This gap upsets the balance between nutrients in the soil causing the sequence of disadvantageous changes.

Alkalization of soil is another disadvantageous occurrence. Alkalization can be caused by cement waste, waste from calcareous, smelly chemical plants, landfill ashes and slags, sewers and urbanized areas. As a result of the alkalization of the soil a concentration of nitrates is growing. It causes delayed plant ripening, their weakening and the associated reduction of their resistance to vermin and illnesses.

Salting the soil is the process of salts accumulation in the soil profile as a result of natural weather conditions or improper irrigation [5]. It is triggered by water-soluble salts, mainly sulphates, chlorides, sodium carbonates. It adversely affects the flora to a great extent since it hampers or completely stops the consumption of water through the root. At the setting of 0.3% and concentration of 0.5%dying out of plants starts taking place [5]. Withering of leaves or dying of roadside trees is the most frequent manifestation of salinity as the effect of exaggerated application of salt in winter in an attempt at the liquidation of black ice. The exaggerated salinity also causes erosion by knocking deep-sea waters, containing waste disposal NaCl off to rivers, which because of the great solubility easily make it out to soil environment and waters. Since the concentration of salt is dependent on the amount of water in soil, salinity is not a permanent phenomenon.

Another danger is environmental pollution of soil with toxic elements. The toxic effect of a substance can result in greater concentration of components of poisonous character. To the most dangerous ones belong heavy metals, herbicides, petroleum products, WWA.

Heavy metals pass through the entire food chain and gradually accumulate in it. The toxicity of heavy metals results from the degree of the contamination of the environment and the biochemical role they fulfill in metabolic processes. The environmentally most hazardous ones are: cadmium, lead, mercury, zinc, copper, chromium and arsenic. These elements enter mainly through dusts emitted from the combined heat and power plants and factories and falling down into the soil. In trace amounts they have a stimulating effect on the growth of plants, however in higher quantities they lead to their dying out [6,14].

Soil often gets contaminated with petroleum and its products, especially in places gas and petroleum obtainment, surroundings of refinery and as a result of the breakdown while storing fuels. Soil pollution with petroleum-derived products adversely affects the crop production.

At present in soils increased contents of long-lasting organic pollutants are recognized, and the frequently observed pollutant is WWA. These compounds come from natural and anthropogenic processes.

Applying herbicides in too large doses, at wrong weather conditions and at incorrect development phases can cause plant damaging.

The process of soil self-cleaning is the longest with reference to long-lasting components. It depends, among others, on the kind of pollutant, the degree of contamination, and the kind of soil.

We distinguish three main methods of soil cleaning to:
 extraction and separation of pollutants from soil with

- the help of water solutions,
- thermal processing consisting in the burning of pollutants or treatment with infrared radiation,
- biodegradation [5].



Fig. 1. Opencast mine of the lignite coal Rusko-Jaroszów [A. Kowalska]

# DIRECTIONS OF RECLAMATION AND DEVELOPMENT

Reclamation not always means restoring ground to its original condition but according to the principle of the forming of diversified environmental conditions can be conducted in other, more desired directions [7]. Degraded areas are often characterized by peculiar properties which, through appropriate actions, can become more attractive and benefit a lot. Therefore, there is no ready standard of behavior with this type of areas, but one should carry out a thorough analysis of all the factors. At first, one should determine the current functions of the area performed before the decline, to recognize the character and scale of ground degradation in order to determine the appropriate functions of the area intended for reclamation. Here are the main factors on which the choice of direction of the reclamation depends:

Landscape features. Especially vertical shaping enjoys a considerable influence on the direction of reclamation. Technical and economic aspects of the performance of works depend on the gradient. A steep slope predisposes degraded areas to direction of the reclamation in which the terrain has a lower significance or for which varied vertical landscape features are necessary.

The area of devastated ground and the kind of surroundings. Small sizes are predisposed to the direction of reclamation in accordance with the kind of surrounding ground. If the surrounding ground is being used in agricultural or forest way, the direction of reclamation should be identical in order to keep the spatial structure of the use. In the vicinity of the building land, recreational or cultural directions are recommended [4,10].

Water relationships. Apart from vertical landscape features, from economic reasons, water conditions have a considerable influence on the direction of reclamation. On heavily watered areas, water direction is proper if necessary, i.e. when the conditions make it a right, natural direction.

**Coating with tree flora and greenery.** Direction of reclamation should be selected in such a way as to integrate the existing flora. However, the flora does not condition the specific direction of reclamation. It participates, however, in creating the biologically active layer of soil needed in reclamation, mainly in agricultural or forest directions.

The type of soil has a considerable influence on the direction of reclamation, particularly when a layer of biologically active soil is essential. On sandy soil, planting the coniferous forest is recommended; sandy, clay, dust and argillaceous soils can be reclaimed in agricultural direction.

It is possible to reclaim a degraded area in a few directions. The most often chosen directions are forest and agricultural ones. In 2009 they amounted to 93% of the whole reclaimed ground [2].

Agricultural direction. The reclamation involves devastated areas which stay in the agricultural category of arable land and are laid for the use as e.g. pastures. Works are focused on the improvement in the biological properties of active soil or its reconstruction, but also on the improvement in water relationships and landscape features.

**Forest direction.** In forest direction laying the ground for the arboriculture is the purpose of reclamation. Reclamation works consist in landscape features improvement, creating the layer of soil and regulating water relationships.

**Fishing direction.** If the reclaimed area has a proper shape, lowering the permeable bottom and the possibility of keeping the essential water level can be used to form fish ponds. Reclamation works consist mainly in the proper forming of the bottom, forming edges and ensuring the essential water level. For example postmining excavations can be used, incurred after extracting sands and gravels, which are usually characterized by the highest level of waters.

**Recreational direction.** It is one of more expensive directions on account of a lot of works needed in order to get a safe and attractive area. In a majority of cases a body of water for recreational purposes is involved.

In order to allow the degraded area to serve people, one should form the bottom of the container, its edges, ensure the appropriate level and quality of water, as well as prepare the grounds for pedestrians, build car parks and roads. In case of the allocation for pedestrian areas, forming the terrain, regulating water conditions and producing the layer of biologically active soil are included in the scope of works.

Land improvement direction. We distinguish two subtypes: hydro-drainage and phyto-drainage. In the first case a small pond serving as a small retention container is created, in the second, afforesting mid-field [1].

**Infrastructure direction.** As a result of reclamation in the direction of infrastructure, devastated areas are converted into economic, housing, building and other types. The works focus mainly on the proper landscape features, draining and preparing access roads. If the area is to be developed in this way it must fulfill a number of conditions such as: endurance of ground, appropriate terrain as well as appropriate water conditions [1].

The essential system of the marking of directions introduced to the reclamation in the PN-G- 07800 norm, 2002 has been supplemented and extended. Apart from trends, also detailed directions were set, which it is possible to survey in order to get all sorts combinations. Such solution was suggested by U. Kaźmierczak and J. Malewski and mentioned in the work by P. Kasprzyk [7].

Trend of the reclamation	Detailed direction of the reclamation	Trend of the reclamation	Detailed direction of the reclamation
Agricultural	cultivations		nature reserve
Agricultural	breeding		landscape park
	economy	Natural	area of protected landscape
Forest	protection		species protection
	recreation		natural feature of historic importance

 Table 2. General and specific reclamation directions by

 Kaźmierczak [1,9]

Water	buildings		documentary position of geological features	
	recreation	Natural	ecological use	
Economic	the housing industry	Tutului	natural- landscape team	
Economic	industry		the green helt	
	services		the green ben	

For areas with a large surface, wider general and detailed directions of the reclamation and development were drawn up. Cultural direction in which the artistic, teaching and contemplative initiative is contained is a novelty.

Tabl	e 3.	General	and spe	ecific d	lirections	of recl	amation
and de	evelop	pment of	terrain-	space of	componer	nts [8]	

	breeding: of animals, poultry, fish		
Agricultural	cultivations: arable land, orchards, meadows, pastures, home-grown gardens		
	protection		
Forest	economic		
	recreation: tourist routes, couples, walking- bicycle paths, health, forest paths promotional complexes		
	recreation: bathing beaches, water sports		
Water	economic: holding containers, containers of the drinking water		
Natural	forms of protection depending on natural values		
	the housing industry, campuses, garages		
	industry		
Economic	services: incubators, magazines, shops, wholesale companies, car parks, sports facilities and the like		
	landfill sites		
	teaching: thematic tracks, laboratories		
Cultural	contemplative		
	artistic: museums, exhibitions, showrooms and concert, stages, amphitheatres and the like		

# METHODS OF THE RECLAMATION OF DEGRADED AND VANDALIZED AREAS

The reclamation consists in sending or restoring the degraded or vandalised utility or natural ground through due forming of the terrain, regulating water conditions, reconstructing the soil, improvement of the physical and chemical properties. The technique of the reclamation of degraded or vandalised areas depends very much on many factors resulting both from the character of reclaimed ground and from the scope of works essential for the set direction of rehabilitation. We distinguish three phases of reclamation of degraded areas: preparatory, technical and biological.

In the preparatory phase the recognition of determinants takes place, consideration of the correctness of performing the reclamation, establishment of the direction of reclamation and development, drawing up and estimate of the technical documentation.

They fall within the scope of the technical phase of reclamation: forming of the relief of the reclaimed area, regulation of water conditions (including the structure of necessary facilities and hydro-technical devices), neutralization of toxic pollutants in the ground, fertilizing works, complete or partial reconstruction of the soil profile and the building of necessary infrastructure [8,15].

The biological phase consists in improving the physical and chemical biological properties of ground and waters, the technical and biological structure of hillsides of heaps and escarpments of excavations, implementing the flora, reconstructing biological conditions and protecting against the sheet erosion of the reclaimed areas as well as storing water in the post-mining holes intended to become bodies of water [1]. The biological reclamation also includes agrotechnical treatments such as: mechanical cultivation of ground, mineral fertilizing, inserting carious blends, mainly papilionaceous and digestive ones.

The role of flora in the process of the reclamation is significant and relies on the protection of areas against industrial pollutants, stabilization of loosely-knit soilgrown works and protection against water erosion and air. Flora also plays an important role in processes of soil formation.

# CONCLUSIONS

According to the Polish constitution and the Act on the protection of agricultural and forest lands every citizen is obliged to look after the natural environment, including ground. However, human activity is connected with interference in the environment and its decline. Deterioration of the state of biologically active layer of soil results from acidification, getting barren, alkalization, salinity, upsetting the balance between nutrients and environmental pollution of soil with toxic elements. A number of developed and tested techniques enabling to obtain optimal conditions for the life of plants and animals exists which, applied during the process of reclamation, can bring notable benefits to the areas in question. We are singling out some of the directions of reclamation. In Poland, agricultural and forest direction is the commonest. There are some main factors on which the choice of reclamation direction depends: landscape relief, area and kind of devastated ground as well as the kind of surroundings, forming the coverage with tree flora and greenery, water conditions or type of works in the degraded area.

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- Ustawa z dnia 3 lutego 1995 roku o ochronie gruntów rolnych i leśnych.

# KIERUNKI REKULTYWACJI I ZAGOSPODAROWANIA NIEUŻYTKÓW

S tr e s z c z e n i e. W publikacji przedstawiono zagadnienia związane z rekultywacją i zagospodarowaniem terenów zdegradowanych. Scharakteryzowano przyczyny degradacji gruntów prowadzące do powstania nieużytków oraz kierunki ich rekultywacji. Przy wyborze kierunku rekultywacji bierze się pod uwagę założenia planu zagospodarowania przestrzennego, potrzeby lokalne oraz zasady ochrony środowiska. Najczęściej wybierane są kierunki rolny i leśny. Istotą przeprowadzenia rekultywacji w tych kierunkach jest całkowite lub częściowe odtworzenie profilu glebowego.

Przez ostatnie dziesięciolecia wyłączonych z użytkowania zostało wiele gruntów rolnych. Przeznaczone były głównie na tereny osiedlowe, przemysłowe, pod drogi i szlaki komunikacyjne, pod użytki kopalne oraz pod zbiorniki wodne. Jednocześnie dzięki rekultywacji i następującemu po niej zagospodarowaniu udało się przywrócić część zdegradowanych, głównie przez przemysł, gruntów pod użytkowanie rolne.

Słowa kluczowe: rekultywacja, zagospodarowanie, nieużytki, degradacja, dewastacja, rolnictwo, gleba, grunt.

# Influence of heating plates temperature on freeze drying energy requirements and quality of dried vegetables

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S u m m a r y. The paper presents the results of research concerning the influence of heating plates temperature of freeze dryer (40, 50, 60, 70°C) on specific drying energy and selected properties of dried vegetables (celery, parsley, carrot). The results showed that an increase of heating plates temperature caused a decrease a specific drying energy (average about 60%), but rehydartion ability and L-ascorbic acid content also decreased. The highest changes of this acid were observed when temperature increased from 60 to  $70^{\circ}$ C. The optimum temperature during freeze drying process of investigated vegetables was  $60^{\circ}$ C.

Key words: lophylization, drying, specific energy, quality, vegetables.

# INTRODUCTION

Freeze drying of foods is one of the best methods of water removal which results in the highest quality of final product. The freeze drying process was first used to food products after the Second World War, in order to preserve and store foods without the refrigeration. Vegetables, fruits, fish, meats, dairy products, herbs and food flavourings can be successfully lyophilized [10,14]. Low temperature during freeze-drying stops microbiological activity and thus the quality of the final product is better. Another important advantage is that during this process the various heat-sensitive biological compounds are not damaged [8,9]. This process retains the physical structure of the food product and preserves it for re-hydration at a later date. It is generally accepted that the flavor of freeze dried foods is better than the air dehydrated products [16,19,21]. However due to the process-specific mechanisms, time of drying and the costs of system is viewed as one of the most energy-consuming food preservation methods [3,12,18]. Thus generally the use of freeze drying in the food industry is limited.

The sublimation rate is the mass of ice sublimed (kg) per unit time (s), which can be expressed [17]:

$$\frac{dm}{dt} = \frac{P_{ice} - P_c}{R_p + R_s},\tag{1}$$

where: dm/dt is ice sublimation rate (kg/s),  $P_{ice}$  is the equilibrium vapor pressure of ice at the sublimation interface temperature (Pa), and  $R_p$  and  $R_s$  are the dry layer and stopper resistance, respectively, to water vapor transport from the sublimation interface (Pa·s·kg<sup>-1</sup>).

Iturria et al [7] have given the formula (2) for calculation the total energy for frozen drying process of biological material. In the formula (2)  $Q_{total}$  is the total heat transferred to the sample (J),  $T_{sample}$  is the sample temperature (K),  $f_v$  is the radiation view factor,  $\varepsilon$  is the sample surface emissivity,  $\sigma$  is the Stefan–Boltzmann constant (Jm<sup>-2</sup>K<sup>-4</sup>s<sup>-1</sup>),  $A_R$  is the sample radiation area (m<sup>2</sup>),  $T_{sur}$  the average surroundings temperature (K),  $T_{shelf}$  is the shelf temperature (K),  $t_1$  is the starting drying time (s),  $t_2$  is the ending drying time (s),  $h_c$  is the contact heat transfer coefficient (J·m<sup>-2</sup>·K<sup>-1</sup>·s<sup>-1</sup>) and  $A_c$  is the sample contact area (m<sup>2</sup>).

$$Q_{total} = (h_c A_c \int_{t_1}^{t_2} (T_{shelf} - T_{ssmple}) dt + f_v \varepsilon \sigma A_R (\int_{t_1}^{t_2} (T_{sur}^4 - T_{samle}^4) dt.$$
(2)

The temperature of freeze drying process has significant influence both on of dried material quality, time of drying and costs of process [11,13,15,20]. Many studies concerning the increase of freeze drying capacity taking into account minimal energy consumption and good quality of product [1,2,16].

Vegetables are the most readily available sources of important proteins, vitamins, minerals and essential amino acids, in the diet. However due to the high moisture content, vegetables are very perishable with low storage life [4,5,6]. Freeze drying increases the shelf life to between 10 and 20 years of food without altering its reconstituted texture [21]. The aim of this work was to evaluate the influence of heating panel temperature on freeze drying energy requirements and selected quality parameters of dried celery, parsley and carrot.

# MATERIALS AND METHODS

The material for investigation were roots of celery (cv. Makar), parsley (cv. Berlińska) and carrot (cv. Cezaro). Before drying, the raw materials were cut into 10 mm cubes. The process of drying was continued until the mass of the sample reached the constant moisture (5% w.b.). The convection dryer load was 3,5 kgm<sup>-2</sup>. The investigation were carried out at the temperature of freeze dryer plates 40, 50, 60, and 70°C and with the constant pressure in the drying chamber – 63 Pa.

The drying process was conducted using the freeze dryer ALPHA 1-4 (Fig. 1). This dryer consists of a drying chamber, cooling and heating systems, vacuum system, and a control and measuring system. Beside of this, the measuring stand consists of: electronic balance cooperated with Wing v.2.05 program and a electric power meter M4660-M cooperated with software Digiscop v.2.41 [19].



Fig. 1. Lyophilisator ALPHA 1-4: 1 - drying chamber, 2 - ice condenser, 3 - frame with heating plates, 4 - electro-magnetic valve, 5 - vacuum pump, 6 - computer, 7 - aeration valve, 8 - cooling system of ice condenser, 9 - control and measuring system, 10 - heating system, 11 - tensometric balance, 12 - electric meter

The rehydration of dried products was evaluated by ability of water absorption according to PN-90/A-75101/19. The content of L-ascorbic acid in raw material before and after drying was determined according to PN-A-04019:1998.

The measurement of the electrical energy supply to particular subassemblies of the lyophilisator, was registered as the power distribution during the drying process with a sampling constant of 0.5 s.

The total value of energy supplied for particular subassemblies of the lyophilisator during one cycle of drying was calculated by using the numerical integration method and spreadsheet [19].

The specific drying energy was calculated as the total energy supplied to lyophilisator during drying process related to 1 kg of dried raw material.

The investigations were replicated five times for each temperature of heating plates. The obtained data was further subjected to a statistical analysis and the consequent evaluations were analyzed for a variance analysis. Statistical tests were evaluated by using the Statistica 6.0 software (StatSoft, Inc., Tulsa, USA). All the statistical tests were carried out at the significance level of  $\alpha = 0.05$ .

#### **RESULTS AND DISCUSSION**

The longest drying time of vegetables was noted at the temperature of heating plates t = 40°C and the shortest at t = 70°C The longest drying time was 610 min, 570 min and 510 min for celery, parsley and carrot, respectively, whereas the shortest time ranged from 210 min (carrot) to 260 min (celery). For all vegetables, as the temperature of heating plates increased a linear decrease of drying time was observed.

The analysis of variance confirmed that the temperature of heating plates has a significant influence on the drying time. (Tab. 1). An increase of temperature of heating plates caused a significant decrease of drying time for all vegetables (Fig. 2).

**Table 1.** The results of variance analysis of drying time under the influence of temperature of heating plates

1	Variable	Source of variance	Sum of squares within groups	p-value	F-test
I t	Drying ime	Temperature of heating plates	44.99331	7.99E-17	2.724944
	700	·			
	600 I	I			celery
min.]	500	I I	T		parsley arrot
time [I	400		- I _		



**Fig. 2.** The relation between the temperature of heating plates and drying time of vegetables

Raw material	Regression equation	R <sup>2</sup>
Parsley	e = -4.74 t + 28.85	0.9832
Celery	e = -4.54 t + 26.7	0.9810
Carrot	e = -4.12 t + 24.1	0.9778

 Table 2. The regression equations described the influence of heating plates temperature on specific drying energy

**Table 3.** The results of variance analysis of specific drying energy under the influence of temperature of heating plates during freeze drying process

Variable	Source of variance	Sum of squares within groups	p-value	F-test
Specific drying energy	Temperature of heating plates	426.6838	1.9E-47	2.724944



**Fig. 3.** Relation between temperature of heating plates and specific drying energy

The results showed a significant decrease of specific drying energy as the drying temperature increased (average from 22.0 to 9,2 MJkg<sup>-1</sup>) (Fig. 3). It is caused by shortening of drying time. The highest specific drying energy was obtained during drying of celery and the lowest for carrot. The highest decrease of energy utilization was observed when drying temperature of heating plates increased from 50 to 60°C. The relations between drying temperature and specific drying energy were described by linear regression equations (Tab. 2).

The results of variance analysis confirmed that the temperature of heating plates has a significant influence ( $\alpha$ = 0.05) on specific drying energy during lophylization process (Tab. 3).

The results of dehydration rate for dried vegetables were presented on Fig. 4. An increase of heating plates temperature caused a slight but significant and linear decrease of dehydration rate of all vegetables (Tab. 4) The highest changes of rehydration index were obtained for dried celery (12% in the case of extreme temperatures of heating plates)

The roots of celery had the initial moisture content 86.3% and contained average 71.5 mg per 100 g of dry weight of L-ascorbic acid. Whereas the average value of this acid in carrot and parsley was 72.0 and 174.7 mg per

100 g of dry weight, respectively and the initial moisture content 85.4% and 83.8%, respectively.



**Fig. 4.** Relation between temperature of heating plates and rehydration rate

**Table 4.** The results of variance analysis of rehydration rate under the influence of temperature of heating plates during freeze drying process

Variable	Source of variance	Sum of squares within groups	p-value	F-test
Rehydration index of dried material, R/ Rmax	Temperature of heating plates	3420.678	5.85E-81	2.724944

The temperature of heating plates has a little influence on L-ascorbic acid content. However, the increase of temperature form 40°C to 70°C caused a significant decrease of this acid content, average about 13%, 17% and 18% for parsley, carrot and celery, respectively (Tab. ). The highest changes of L-ascorbic acid content (decrease about 8-9%) were observed when drying temperature of heating plates increased from 60 to 70°C (Fig. 5). The changes of L-ascorbic acid in the function of heating plates temperature were described by using the quadratic equations.

**Table 5.** The results of variance analysis of L-ascorbic acid content under the influence of temperature of heating plates during freeze drying process

Variable	Source of variance	Sum of squares within groups	p-value	F-test
L-ascorbic acid content	Temperature of heating plates	791.9623	3.23E-57	2.724944

**Table 6.** The regression equations described the influence of heating plates temperature on L-ascorbic acid content

Raw material	Regression equation	$\mathbb{R}^2$
Parsley	$L = -3.1 t^2 + 8.7 t + 149.6$	0.9934
Celery	$L = -1.65 t^2 + 4.67 t + 60.3$	0.9795
Carrot	$L = -1.25 t^2 + 3.47 t + 47.4$	0.9858



Fig. 5. Relation between temperature of heating plates and L-ascorbic acid content

## CONCLUSIONS

- 1. The specific drying energy during lophylization process of vegetables decreased as temperature of heating plates increased (average from 22.0 to 9,2 MJkg<sup>-1</sup>). The highest decrease of drying energy was observed when temperature increased from 50 to 60°C.
- An increase of heating plates temperature caused a decrease of rehydartion index of dried vegetables. The highest changes of rehydration index (decrease about 12%) were obtained in the case dried celery
- 3. The content of L-ascorbic acid decreased as the temperature of heating plated increased. The highest changes of this acid were observed whet temperature increased from 60 to 70°C.
- According to these results we can conclude that the optimum temperature of heating plates during freeze drying process of investigated vegetables is 60°C.

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# ANALIZA WPŁYWU TEMPERATURY PŁYT GRZEJNYCH LIOFILIZATORA NA ENERGOCHŁONNOŚĆ PROCESU I CECHY JAKOSCIOWE SUSZU Z WYBRANYCH WARZYW

S tr e s z c z e n i e. W pracy przestawiono wyniki badań dotyczące wpływu temperatury płyt grzejnych na energochłonność procesu liofilizacji oraz wybrane cechy jakościowe warzyw (selera, pietruszki i marchwi). Na podstawie uzyskanych wyników stwierdzono, że wzrost temperatury płyt grzejnych powodował spadek jednostkowych nakładów energii suszenia (średnio o 60%). Następowało także pogorszenie wskaźnika rehydracji suszu oraz zmniejszenie zawartości kwasu Laskorbinowego. Największe zmiany tego kwasu odnotowano przy wzroście temperatury płyt grzejnych z 60 do 70°C. Za optymalną temperaturę liofilizacji badanych warzyw przyjęto 60°C.

Słowa kluczowe: liofilizacja, suszenie, energochłonność jednostkowa, jakość, warzywa.

# Fourier transformation – an important tool in vibroacoustic diagnostics

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Summary. The objective feature of the reflection allows for using measurable physical quantities that characterize the processes accompanying the operation of a mechanical device, as signals carrying encoded information. In order to decode this information, the signal has to be retrieved and converted into a characteristic, usually determined in frequency domain. Using the DFT procedure, the computer allows for calculations of the estimates of frequency characteristics. For the effective use of the numerical methods, one needs to know how the information encoded in the signal is generated during its processing. In order to investigate these problems, a model that reflects the A/C conversion and the periodization of the fragment of retrieved signal in a closed time frame was used. The investigation of this model has shown that the DFT procedure generates stripes representing the harmonic waves of a signal only for admissible frequencies, equal to the total multiplicity of the inverse of signal retrieval time. To present the wave of another frequency, the DFT procedure generates a substitute spectrum. Consequently, the discrete spectrums are a result of a superposition of waves representing the harmonic signal components of frequencies that belong to the admissible set as well as waves of frequencies that do not belong to this set and form substitute spectrums.

Key words: vibroacoustic diagnostics, numerical signal processing, Fourier transformation.

# INTODUCTION

For construction and operation of mechanical devices information related to its technical conditions, its properties and processes taking place is necessary. In reference to mechanical devices the obtainment of such knowledge requires a realization of a research process consisting in acquiring and interpretation of information. This is the task of technical diagnostics [4, 5, 9, 10, 11, 14].

A reliable source of information on a mechanical device is research. It is known that 'the matter-characteristic, objective feature of the reflection is shown through generating and conveying information on the conditions of objects of the material world' [17]. This feature allows using measurable physical quantities that characterize the processes accompanying the operation of a device as diagnostic signals carrying encoded information. In order to decode this information the signal has to be retrieved and converted into a characteristic.

Most of the processes occurring in a device in operation that are the sources of the signals are series of events that repeat periodically. That is why the characteristics of these signals are usually determined in the frequency domain.

Computers of high computational power and modern algorithms allow cheap and quick calculations of different, sometimes very complex frequency characteristics of the diagnostic signal through numerical methods. For the effective use of the numerical methods of signal processing one needs to know how the information encoded in the signal is generated during its processing and how the information is distorted and presented in the signal characteristics.

#### THE SUBJECT OF INVESTIGATION

The subject of the investigation is a mechanical device composed of elements joined in kinematic pairs. An operating device can be perceived as a controlled acting system, schematically presented in figure 1. The system is characterized by an open flow of the stream of mass, energy and information that is divided into two components. The first appears at the output in the form of a working process. The other is an uncontrolled stream of mass, energy and information that accompanies this process. In a correctly functioning device the amount of mass and energy in the second component is miniscule in comparison to the mass and energy of the first one. Yet, the flow of information related to the functioning principle is similar to the first component [10, 17].

 $b_n$ 



Fig. 1. Flow of stream of mass, energy and information

The second component of the flow stream appears in the form of processes that accompany the operation of the device. The most important are: deterioration, vibroacoustic and thermal processes. The cause-andeffect relation between the symptoms that characterize the conditions of the device and the processes that take place in this device as well as the relation between the processes emitted to the outside allows using 'reflection' for diagnostic purposes. The physical quantities that characterize these processes are used as signals carrying information on the device.

During the operation sources of wave distortions located in various kinematic pairs and parts of the mechanical device activate. Some of them have been shown in figure 2.



Fig. 2. Sources of wave distortions

The wave distortions generated by the sources, marked with  $x_1(t),...,x_n(t)$  in figure 3 are subject to feedback through propagation. Between the sources and the output of the system representing the investigated device forms a channel of flow of information. At the output of the channel appears signal  $\vec{y}(t)$  whose coordinates are the selected physical quantities [10, 11].



Fig. 3. The channel of the flow of information

In practice, individual time realizations of these quantities are used as diagnostic signals. The amount of information included in realization f(t) depends on its versatility that shows through changes in time. Each change is one bit of information. The higher the frequency

of these changes the more information in a time unit will be conveyed to the output of the flow channel. In this case the vibroacoustic signals (mechanical and acoustic vibrations) are the best choice out of all signal emissions by the operating device. An additional advantage of these signals is their accessibility outside of the device without distorting their operation [2,10, 17].

#### FOURIER TRANSFORM

In 1807, the baron Jean-Baptiste Joseph Fourier, a mathematician, engineer, member of the French Academy presented an essay treating on the fact that periodic, linear function f(t) fulfilling the Dirichlet conditions can be expressed as a sum of series:

$$f(t) = a_0 + \sum_{n=1}^{\infty} \left( a_n \cos 2\pi v nt + b_n \sin 2\pi v nt \right)$$
(1)  
where:  $a_0 = \frac{1}{T} \int_{-T/2}^{T/2} f(t) dt$ ,  $a_n = \frac{2}{T} \int_{-T/2}^{T/2} f(t) \cos 2\pi v nt dt$ ,  
 $= \frac{2}{T} \int_{-T/2}^{T/2} f(t) \sin 2\pi v nt dt$ .

Coefficient  $a_0$  is an average value,  $a_n$ ,  $b_n$  are the coefficients of the harmonic distribution of function f(t). Index  $n=1,2,...,\infty$  denotes the expressions of the series, T – period of function f(t), v=1/T – frequency. Because:  $v_n = vn = n/T$  and  $v_{n+1} = v(n+1) = (n+1)/T$  the increment  $\Delta v = v = 1/T = const$ . Equation (1) presents function f(t) as an infinite sum of cosine and sine functions of discrete frequencies growing by a step of  $\Delta v$ .

We can assume that for the non-periodic function  $T \rightarrow \infty$ , then  $\Delta v \rightarrow dv$ . Taking this assumption into account, after transforming series (1), we obtain a formula for the Fourier Transform [1, 3, 13]:

$$\mathbf{F}(\nu) = \int_{-\infty}^{\infty} f(t) \exp(-j2\pi\nu t) dt$$
(2)

The integral (2) is a functional, in which the nucleus  $\exp(-j2\pi vt)dt$ , in function f(t) seeks a harmonic wave of the frequency of  $v \in [0,\infty)$  and describes it with a complex number, containing the time-averaged  $t \in (-\infty,\infty)$  information on the amplitude and phase of this wave. In the complex coordinate system this number determines the point that is the end of a vector (in this paper the complex values will be typed in bold):

$$\mathbf{F}(v) = a(v) + jb(v) \tag{3}$$

of the phase module and angle:

$$\left|\mathbf{F}(v)\right| = \sqrt{a^2(v) + b^2(v)} \tag{4}$$

$$\Psi(v) = arctg[b(v)/a(v)] + \pi m$$
, where  $m = 0, \pm 1, \pm 2, ...$ .

Vector  $\mathbf{F}(v)$  presented in figure 4 is a spectrum of the harmonic wave of frequency  $v_n$  contained in function f(t). Because operation (2) of the transformation of function f(t) is repeated for all frequencies from the range  $[0,\infty)$ , transform  $\mathbf{F}(v)$  show the course of signal f(t) in the frequency domain.



**Fig. 4.** The spectrum of the harmonic component of function f(t)

Using the phase module and angle from dependence (4), equation (3) can be notated according to the Euler theorem in the trigonometric form:

$$\mathbf{F}(v) = |\mathbf{F}(v)| \cos\psi(v) \pm j |\mathbf{F}(v)| \sin\psi(v) = |\mathbf{F}(v)| \exp[\pm j\psi(v)]$$
(5)

Hence:

$$a(v) = \left| \mathbf{F}(v) \right| \cos \psi(v), -b(v) \left| \mathbf{F}(v) \right| \sin \psi(v)$$
 (6)

In the system of three coordinates: real part a(v), imaginary unit jb(v), frequency v - continuous course of the Fourier transform is a place of the geometrical end of vectors  $\mathbf{F}(v)$  just like the ones in figure 4, distributed on the axis of frequency every  $dv \rightarrow 0$ . Taking the dependences (4) into account, we can present the transform in the form of two courses: module spectrum  $|\mathbf{F}(v)|$  and spectrum of the phase angle  $\psi(v)$ .

Time realization f(t) is always a real function of time. The results of the Fourier transformation of such a function will be a complex transform. Knowing the course of the cosine and sine functions we can prove that a(v)=a(-v) and -b(v)=b(-v). The Fourier transform of the real function fulfills the Hermite conditions. This means that the real part is even and the imaginary unit is odd. As a consequence the course of the module is an even function:  $|\mathbf{F}(v)| = |\mathbf{F}(-v)|$  and the course of the phase angle is an odd function:  $-\psi(v) = \psi(-v)$  [1, 3].

Time realization f(t) and Fourier transform  $\mathbf{F}(v)$  remain in the equivalence relation. The equivalent pair  $f(t) \Leftrightarrow \mathbf{F}(v)$  fulfills the theorems of linearity and additiveness and mutual symmetry. The transform of the product of two functions  $f_1(t) \cdot f_2(t)$  equals to the wreath product (convolution) of their transforms  $\mathbf{F}_1(v)^*\mathbf{F}_2(v)$ ; the reverse theorem is also true.

# THE MEASUREMENT WINDOW

An infinite period of function f(t) manifests through infinite boundaries of integration of transformation (2). In diagnostic research of mechanical devices we retrieve a fragment of a signal  $f(t): t \in [-T/2, T/2]$ . The finite retrieving time *T* becomes a basic period of function f(t)and determined the frequency of the periodization of the retrieved fragment:  $v_T = 1/T$ . This is contrary to the assumption that  $T \rightarrow \infty$  for non-periodic function f(t) that the basis for the transformation of series (1) to the form of an integral (2) [1, 6, 8, 10].



Fig. 5. Diagnostic signal in the measurement window

Range [-T/2, T/2] determines a rectangular measurement window such that: w(t) = 1 for  $t \in [-T/2, T/2]$  and w(t) = 0 for  $t \notin [-T/2, T/2]$  presented in figure 5. The Fourier transformation is performed on signal  $f(t): t \in [-T/2, T/2] = [f(t): t \in (-\infty, \infty)] \cdot w(t)$ :

$$\int_{-\infty}^{\infty} [f(t) \cdot w(t)] \cdot \exp(-j2\pi vt) dt =$$

$$= \int_{-T/2}^{T/2} f(t) \cdot \exp(-j2\pi vt) dt = \mathbf{F}(v)^* \mathbf{W}(v)$$
(7)

where the transform of the rectangular measurement window was w(t):

$$\mathbf{W}(v) = \int_{-\infty}^{\infty} w(t) \exp(-j2\pi vt) dt = \int_{-T/2}^{T/2} \exp(-j2\pi vt) dt = T \frac{\sin \pi vT}{\pi vT}$$
(8)



Fig. 6. Transform of the rectangular measurement window

The course of the transform  $\mathbf{W}(v)$  for v=0, presented in Figure 6, is suspended on the abscissa of the coordinate system. If signal f(t) contains harmonic component of this frequency and amplitude that equals one then this component should manifest in figure 6 in the form of a stripe of module spectrum  $|\mathbf{F}(v)|$  on the ordinate. Because the signal was retrieved in finite time *T*, then as a result of the convolution (7) the stripe of the spectrum will be represented by local maximum of the course **W**(*v*) for *v*=0. Because for *v*→0  $\lim \frac{\sin \pi vT}{\pi vT} = 1$  value *T* determines the scale that will adjust the height of this maximum against the length of the stripe.

In the spectrum of the module of the actual signal, the stripes denoting the amplitudes of the individual harmonic components occur for different frequency  $v_n$ , where n=1,2,3,... The expression (8) will take the form:

$$\mathbf{W}(\nu) = T \frac{\sin \pi (\nu - \nu_n) T}{\pi (\nu - \nu_n) T}$$
(9)

The stripe of the module spectrum for  $v = v_n$  will be distorted by the rectangular measurement window identically as the stripe for v=0.

The rectangular measurement window effect shows as a leakage and lateral waves of the Fourier transform of signal f(t):  $t \in [-T/2, T/2]$ . The leakage makes the differentiation of the neighboring stripes difficult and sometimes impossible and the lateral waves distort their value.

# THE PROCESSING PRINCIPLES OF VIBROACOUSTIC SIGNALS

The time realization retrieved as a diagnostic signal is in fact an ergodic and stochastic process  $f(\zeta,t)$ , where: t - time,  $\zeta - \text{random variable}$ . In a sufficiently long range function  $f(t): t \in [-T/2, T/2]$  carries encoded information contained in process  $f(\zeta,t)$ . The processing that should enable reading of this information consists in determining of the non-random characteristics from function  $f(t): t \in [-T/2, T/2]$ . It is assumed that in range [-T/2, T/2]this function is linear, stationary and fulfills the Dirichlet conditions [1, 10].

The characteristics can describe signal f(t):  $t \in [-T/2, T/2]$ in three domains: value, time and frequency. In the diagnostic of mechanical devices the most frequent sample is the one consisting in transformation of the signal to the frequency domain with the use of the Fourier Integral. This is particularly the case in vibroacoustic signals.

Equivalence  $f(t) \Leftrightarrow \mathbf{F}(v)$  means that the following relation is true:  $|f(t)|^2 \Leftrightarrow |\mathbf{F}(v)|^2$ . The squared course of the module spectrum is a frequency image of the energy contained in signal f(t) and carries information of the intensity of the wave distortions that were activated while the mechanical device was in operation. This information, read and properly interpreted may form a message regarding the technical condition of the parts and kinematic pairs of the device where these sources are located [2, 10].

The sources of distortions are characterized by periodic repeatability of reversible events that manifest as wave phenomena. The values of frequencies determined based on the knowledge of the system composition and structure represented by the device can be deemed as common addresses of spectral components and sources that generated it. The addresses of a given pair source-component are usually different for each pair. The information resulting from relation  $|f(t)|^2 \Leftrightarrow |\mathbf{F}(v)|^2$  regard-

ing the value of the module of the spectral component of the signal is at the same time information regarding the energy resulting from the intensity of functioning of a given source of distortion. The schematics of the conveyance channel presented in figure 3 shows that signal  $f(t):t\in[-T/2, T/2]$  carries information regarding the energy of different sources that are mixed due to mutual feedbacks. Course  $|\mathbf{F}(v)|$  depicts the frequency decomposition of the signal that allows identifying and estimating the energy generated by given sources. That is why the Fourier transformation is an important tool in signal processing used in vibracoustic diagnostics of mechanical devices.

The computers allow calculations of the estimates of different characteristics that are difficult to determine through direct analogue measurement. The Fourier spectrum is a perfect example here. The database for the calculations of the spectrum is a series of values representing continuous time realizations of signal fragment  $f(t): t \in [-T/2, T/2]$  [10, 11, 16].

### MODEL OF A DISCRETE SIGNAL

The retrieved time realizations  $f(t): t \in [-T/2, T/2]$  are continuous. A series of values from which the computer will calculate the Fourier transform is generated in two phases by the A/C converter from the retrieved signal:

- 1. sampling that consists in discretization of the function argument:  $f(t): t \in [-T/2, T/2]$  in moments:  $t_0, t_1, ..., t_k, ..., t_{N-1} \in [-T/2, T/2]$ . The difference:  $\Delta t = t_{k+1} t_k = T_e$  determines the constant period of sampling and the frequency of sampling:  $v_e = 1/T_e$ . Values *T* and  $T_e$ , determine the number of samples:  $N = T/T_e =$ int. that will fit into the measurement window,
- 2. quantization of realization  $f(t): t \in [-T/2, T/2]$  in moments:  $t_0, t_1, \dots, t_k, \dots, t_{N-1}$  that determines the value of signal  $f(kT_a)$  for:  $k=0,1,2,\dots,N-1$ .

The discrete function:  $f(kT_e)$  represents a series of subsequent events each of which has an assigned number value. Separately, none of them carries any important information, but a series of N – events in timely order, does. In the database obtained during the A/C conversion information is stored regarding the signal in the measurement window in the moment of sampling. Other information that can exist in the signal is lost.

In order to analyze the process of generating the information during numerical processing we can use a model that reflects the A/C conversion and the periodization of the fragment of the retrieved signal in a closed time frame [10, 12,15]. For the creation of such a model we can use the Dirac comb:

$$III(t) = \bigcup_{\alpha = -\infty}^{\infty} \delta(t - \alpha T_e), \text{ where } \alpha = -\infty, ..., -1, 0, 1, ..., \infty,$$

shown in figure 7a. It is a series of impulses evenly distributed on the time axis maintaining a distance equal to signal sampling period  $\Delta t = T_e$  =const. The multiplication by the function of window w(t) takes into account the

retrieval of the signal of the period of [-T/2, T/2] and limits the number of samples determined by the Dirac impulses to the value *N*:

$$f^{\bullet}(kT_e) = (f(t): t \in (-\infty, \infty)) \cdot \cdots \\ \cdot w(t) \cdot \bigcup_{\alpha = -\infty}^{\infty} \delta(t - \alpha T_e)$$
(10)

The periodization of signal (10) we can reflect through convolution of signal  $f^{\bullet}(kT_e)$  through Dirac comb III'  $(t) = \bigcup_{\eta=-\infty}^{\infty} \delta(t-\eta T)$  in which the impulses are distributed on the time axis every  $\Delta t = T = \text{const.}$  and are numbered with an index:  $\eta = -\infty, ..., -1, 0, 1, 2, ..., \infty$ :

$$f(kT_e) = (f(t): t \in (-\infty, \infty)) \cdot \cdots$$
$$\cdot w(t) \cdot \bigcup_{\alpha = -\infty}^{\infty} \delta(t - \alpha T_e) * \bigcup_{\eta = -\infty}^{\infty} \delta(t - \eta T)$$
(11)



Fig. 7. Dirac comb in the time and frequency domain

Signal  $f(kT_e)$  for k=0,1,2,...,N-1 is a series of events that is why operations (10) and (11) marked  $\bigcup$ , are not algebraic addition but a summing of events.

#### DISCRETE FOURIER TRANSFORM

Taking into account the theorem on the transform of the algebraic product and convolution of two functions the Fourier transformation of signal  $f(kT_e)$  can be notated as follows:

$$\mathbf{F}(v) = \left[\int_{-T/2}^{T/2} f(t) \exp(-j2\pi vt) dt \right] \cdot \int_{-\infty}^{\infty} [\Pi I'(t)] \cdot \exp(-j2\pi vt) dt + \int_{-\infty}^{\infty} [\Pi I'(t)] \cdot \exp(-j2\pi vt) dt \quad (12)$$

The Fourier integral from -T/2 to T/2 takes into account the algebraic multiplication through window w(t). The result of the integration is the convolution of the function  $f(t) \in (-\infty,\infty)$  transform and the transform of the rectangular measurement window occurring on the right side in formula (7).

The Fourier transform of the Dirac comb that is determined in the time domain remains the Dirac comb in the frequency domain [15]. It has a form of distribution of a period of  $1/\Delta t$ , shown in figure 7b. The transforms III(*t*) and III'(*t*) will be respectively:

$$\mathbf{III}(v) = v_e \bigcup_{\alpha = -\infty}^{\infty} (\delta - \alpha v_e), \ \mathbf{III}'(v) = v_T \bigcup_{\eta = -\infty}^{\infty} (\delta - \eta v_T),$$

where:  $v_e = 1/\Delta t = 1/T_e$ ,  $v_T = 1/\Delta t = 1/T$  and  $\alpha, \eta = -\infty, ..., -1, 0, 1, ..., \infty$ .

Algebraic multiplication through comb III'(t) will result in a discretization of the spectrum to the form of a series of vectors referred to as stripes. Value  $v_T = 1/T$ determines a constant distance between the stripes and determines the discrete spectrum resolution. The values  $\eta v_T$  determine frequencies for which these stripes can appear. The rectangular measurement window limits the number of stripes to value N.

The convolution by  $\mathbf{III}(v)$  results in a periodization of the discrete spectrum. It is shown as a reproduction of the spectrum every  $v_e$  value for an infinite number of times because  $\alpha = -\infty, ..., -1, 0, 1, ..., \infty$ . Frequencies  $v_r$  and  $v_e$ , occurring before the sums of events in the transforms of the Dirac combs  $\mathbf{III}'(v)$  and  $\mathbf{III}(v)$  determine the scale of the multiplication operation and do not influence the way the discrete spectrum is formed.

Figures 8a, b and c show the process of the formation of the discrete spectrum of the module of the tested signal represented by the real function of time.

According to the Hermit conditions, the spectrum of the module of the real function is even. In figure 8a spectrum  $|\mathbf{F}(v)|$  and its even reflection  $|\mathbf{F}(-v)|$  are symmetrical and form a unity that as a result of periodization is 'suspended' on the abscissa determined by stripes  $0 \cdot v_e$  and  $1 \cdot v_e$ . The reproduction of the spectrum results in that the information in all ranges  $[\alpha \cdot v_e, (\alpha+1) \cdot v_e)$ , where  $\alpha = -\infty, ..., -1, 0, 1, ..., \infty$  will be the same. That is why for the considerations only one range needs to be included:  $[0, v_e)$ . In this range  $N = v_e/v_T$ , stripes will fit that are numbered with index n = 0, 1, ..., N-1.

In figure 8b spectrum  $|\mathbf{F}(v)|$ , suspended on abscissa  $v_e = 0 \cdot v_e$  and its left hand reflection  $|\mathbf{F}(-v)|$  suspended on abscissa  $v_e = 1 \cdot v_e$  are subject to superposition in frequency range  $[0, v_e)$ . The determined spectrum is a sum of superimposed courses:  $|\mathbf{F}(v)|$  and  $|\mathbf{F}(-v)|$ . This phenomenon is called aliasing.



Fig. 8. Periodization, aliasing and filtering of the discrete spectrum

The middle of range  $[0,v_e]$  is determined by the Nyquist frequency:  $v_{Nyq} = 0.5v_e$ . If in spectrum  $|\mathbf{F}(v)|$  that is suspended on stripe  $0 \cdot v_e$  occurs a local maximum for frequency  $v > v_{Nyq}$  then, due to symmetry, the same maximum will occur in spectrum  $|\mathbf{F}(-v)|$ , suspended on stripe  $1 \cdot v_e$ , for  $v < v_{Nyq}$ . As a result of aliasing in frequency range  $[0,v_{Nyq})$  spectral information will be conveyed that is not contained in the signal. If we want to avoid that, we should use a low-pass filter of the signal that will damp the harmonic components of frequencies equal or greater than the Nyquist frequencies as shown in figure 8c.

If signal  $f(kT_e)$  determined by formula (11) is subjected to low-pass filtering then in frequency range  $[0, v_{Nyq})$  then at the most N/2 of the stripes of the discrete spectrum will fit that are numbered with an index: n=0,1,2,...N/2-1.

Replacing the integration with addition after k=0,1,2,...N/2-1 and substituting time and frequency in the discrete form from dependence (12) we can derive a formula for the discrete Fourier transform:

$$\mathbf{F}(nv_{T}) = \frac{1}{T} \sum_{k=0}^{N-1} f(kT_{e}) \cdot \exp(-j2\pi n v_{T} kT_{e})$$
(13)

In the dimensionless domain of indexes k and n, transformation (13) takes the form of Discrete Fourier Transform (DFT):

$$\mathbf{F}(n) = \frac{1}{N} \sum_{k=0}^{N-1} f(k) \cdot \exp(-j2\pi nk/N)$$
(14)



Fig 9. Signal discrete spectrum

Dependence (14) shows a system of equations for n=0,1,2,...N/2-1. The results of the solution of each equation is transform  $\mathbf{F}(n)$  in the form of a complex number that determines the module and phase angle of a single stripe of a spectrum for frequency  $nv_{T}$ . The whole spectrum is a sum of harmonic components of a signal occurring on the frequency axis for values  $nv_{T}$ :

$$\mathbf{F}(\boldsymbol{v}_n) = \bigcup_{n=0}^{N/2-1} \mathbf{F}(n)$$
(15)

Figure 9 presents the signal discrete spectrum calculated from the DFT dependence.

# SPECTRUM OBTAINED THROUGH THE DFT METHOD

While generating spectrum  $\mathbf{F}(n)$  of signal f(k) the discretization with period  $T_e$  results in a periodization of the spectrum with period  $v_e = 1/T_e$ . Sampling frequency  $v_e = 1/T_e$  determines band  $[0, v_{Nyq} = 1/2v_e$  where the stripes of the discrete spectrum are contained.

The periodization of the signal f(k) with period T results in a discretization of the spectrum with resolution  $v_T = 1/T$ . The DFT procedure generates stripes only for admissible frequencies  $nv_T$  of values equal to the total multiplicity of the inverse of signal retrieval time. The strips carrying original information on the harmonic components of the signal, are numbered with index n=0,1,2,...,N/2-1.

The frequency structure of the signals generated by the sources of wave distortions that function in mechanical devices is unknown. The frequencies of the harmonic components that form the signal depend on the physical nature of the sources and they are independent from value T and  $v_e = 1/T_e$ . That is why we should expect that the frequencies of many components (possibly all) of the retrieved signal would not belong to the admissible set [7, 10, 11].

Figure 10a shows the signal in the form of a harmonic wave that was subjected to a discrete Fourier transformation. Because the retrieval time  $T = n \cdot T_{th}$  where n = 2 and  $T_{th}$  - the period, the frequency of the wave belongs to the admissible set. The spectrum of the module, presents the stripe for n=2 shown in figure 10b. The reduction of time T results in that  $T \neq n \cdot T_{fh}$  and frequency  $v_T = 1/T$ of the wave does not belong to the admissible set. In order to present this wave the DFT procedure generates a substitute spectrum in the form of a set of waves of admissible frequencies that do not exist in the signal. The local maximum of the substitute spectrum shown in figure 10c occurs for admissible frequencies close to the value of  $1/T_{th}$ . We can expect that the result of the superposition of waves of the substitute spectrum will be the approximate course of the signal.



Fig. 10. The signal, its real and substitute spectrum

The analysis of the results presented in Figure 10 gives grounds for a formulation of the following hypothesis: the waves of the discrete substitute spectrum are determined by the DFT procedure according to the Fourier series for a preset and limited set of admissible frequencies  $nv_T$ . The trueness of the hypothesis can be verified through comparing the spectrum of the signal obtained from the development into a Fourier series with the spectrum of this signal calculated with the DFT method.

After a transformation of the sum of the cosine and sine function in formula (1) the Fourier series can be notated in the form of a sine function taking into account the phase angle:

$$f(k) = \sum_{n=0}^{N/2-1} A_n \sin\left(\frac{2\pi nk}{N} + \psi_n\right)$$
(16)

In series (16) function f(k) where k=0.1,2,...,N-1represents a discrete form of the investigated wave  $f(t)=A\sin 2\pi vt$  retrieved in finite time *T*. The argument of the sine function determines the dimensionless domain of admissible frequencies that belong to range  $[0,v_{Nyq})$ marked with index: n=0,1,2,...,N/2-1. In comparison to series (1), in formula (16) the summing was limited to N/2 of the components. Symbol  $\psi_n$  denotes the phase angle of the *n*-th component of function f(k).

Because in the experiment T=const was assumed, the set of admissible frequencies preset for the development of function f(k) will be constant. In order to obtain information that could confirm (or reject) the assumed hypothesis one should investigate different substitute spectrums. To this end we need to ensure the possibility of modification of the wave frequency without changing the retrieval time.

Let wave frequency  $v = (1+\varepsilon)/T$ . Then for  $\varepsilon = 0 - a$  single wave period equals *T* and its frequency  $v \equiv v_T = 1/T$ . For each value  $\varepsilon \in (0,1)$  maintaining a constant retrieval time the frequency of the wave will not belong to the admissible set. After substituting the dependence:  $v = (1+\varepsilon)/T$ ,  $T = NT_e$  and  $t = kT_e$ , the argument of the sine function in formula (16), assumes the form  $2\pi(1+\varepsilon)k/N$ . Then:

$$f(k) = A\sin 2\pi (1+\varepsilon)\frac{k}{N}$$
(17)

Wave f(k) has been determined for A=1 and N=16 samples numbered with index: k=0,1,2,...,15. The modified wave presented in figure 11 was generated for:  $\varepsilon = 2/3$ . Taking the Nyquist criterion into account the spectrum was determined for N/2-1 of the frequencies marked with index n=0,1,...,7.

Substitute spectrums of the module of the investigated wave calculated from the Fourier series and through the DFT method have been presented in figure 12. The stripes superimposed on the admissible frequency mesh show a spectrum obtained from formula (16) and the stripes in the immediate vicinity through the DFT method. The height of the stripes obtained with two methods is identical, which is confirmed by the adopted hypothesis.

## DISCRETE SPECTRUM DISTORTION

The average value of the original wave of  $\varepsilon = 0$ , represented by the component of the spectrum for n=0, equals zero. The performed modification of the frequency of this wave results in an unintended and incidental change of the average value of the retrieved fragment of the signal. That is why in the substitute spectrum in figure 12 the stripes for n=0 are non-zero.



**Fig. 11.** Wave for  $\varepsilon = 2/3$ 



Fig. 12. Discrete wave spectrums for  $\varepsilon = 2/3$ 



Fig. 13. Discrete wave spectrums for  $\varepsilon = 2/3$  after resetting of the average value

In figure 11 the axis of abscissa has been shifted so that the average value of the fragment of the wave for  $\varepsilon = 2/3$  equaled zero. Figure 13 presents the courses of the discrete spectrum of the module of this fragment of the wave after shifting the axis of abscissa. The component of the spectrum for n=0 equals zero and the stripes representing the outstanding components are the same as in figure 12 before the shift has been carried out.

From the course of transform  $\mathbf{W}(v)$  in figure 6 and dependence (8) results that for the admissible frequencies  $n/T = nv_T$  when n = 1, 2, ... = int, complex integer  $\mathbf{F}(v)^*\mathbf{W}(v)=0$  because  $\mathbf{W}(v)=0$ . For n=0, this product is other than zero and the transform of the window influences the stripe of the spectrum through change of the scale. Formula (9) confirms that this statement is correct for each stripe of the spectrum irrespective of value  $nv_T$  for which it occurred on the condition that n=int.

Because in the discrete spectrum the total multiplicity of the inverse of the retrieval time determines the set of admissible frequencies, the discretization of the spectrum eliminates the distortions triggered by the rectangular measurement window in the form of a leakage and lateral waves. The filtering characteristics of periodical distribution  $\mathbf{III}'(t)$  starts manifesting itself. Because dependence (7) remains true we can assume that the distortions of the discrete spectrums from the rectangular measurement window would display themselves in a different form than it directly results from this dependence.

In order to estimate the transfer of the information the original harmonic waves has been reproduced from the substitute spectrum. Figure 14 presents the comparison of the course of the wave generated for  $\varepsilon = 2/3$  and the course of the wave that was a result of a superposition of the harmonic waves recovered from the stripes of the substitute spectrum. Figure 15 shows the residuum determined by the difference between the recovered and the original wave.



Fig. 14. The original and recovered waves for  $\varepsilon = 2/3$ 



Fig. 15. Residuum of the original and recovered waves for  $\varepsilon = 2/3$ 

#### CONCLUSIONS

The discrete spectrums generated and emitted by mechanical devices in operation are a result of a superposition of waves representing the harmonic components of the signal of frequencies that belong to the admissible set as well as waves of frequencies that do not belong to this set and form substitute spectrums. Thus resulting distortions of the discrete spectrum are consequence of the existence of a rectangular measurement window of retrieval time of T.

The DFT procedure generates a substitute spectrum according to the Fourier series irrespective of the researcher's intention. The stripes of the spectrum are determined for admissible frequencies that belong to a limited range. The values of these frequencies and the boundary frequencies of this range are preset and determined by values *T* selected by the researcher. The substitute spectrum transfers approximately true frequency information in the form of a sum of untrue information that is not in the signal. The amount of information is limited by the width of the range  $[0, v_{Nyq})$ .

The superposition of the waves of the substitute spectrum, taking the phase shifts into account, recovers the course of the harmonic wave. The courses of the residuum determined from the comparison of the original wave and the same wave obtained from the substitute spectrum shows that the recovery is inaccurate and incomplete. This mainly results from the fact that the recovered wave is a result of limited number N/2 – waves of the substi-

tute spectrum contained in frequency range  $[0, v_{Nyq})$  not a infinite number of waves as the Fourier series requires.

The finite retrieval time, selected by the researcher, results in the fact that the average value of the processed fragment of the signal is mostly non-zero. The information transferred by the stripe of the discrete spectrum for n=0 is incidental and thus unreliable. The distortion of the spectrum from the constant component can be eliminated by assuming this value to be zero by definition. From the courses of the residuum we can see that the wave recovered from the components of the substitute spectrum was more accurate as compared to the original wave. Such an action does not trigger a change of the components for n>0 and does not generate additional spectrum distortions.

The existence of the measurement window, which is an inevitable consequence of the limited retrieval time, as well as discretization of the signal during the A/C conversion are in opposition to the assumptions based on which from series (1) Fourier integral was derived (2). That is why the described distortions of the discrete spectrum are inevitable and with today's level of knowledge cannot be eliminated nor reduced through adjustment windows used when determining the spectrums with analogue methods (spectrometers).

Each adjustment window is a function of weight. The signal multiplied by this function assumes a zero value at the beginning and at the end of the retrieval. This multiplication results in deletion of some information contained therein and addition of other, carried by the window function not contained in the signal. Product (7) assumes a form  $\mathbf{F}(v)*\mathbf{W}_k(v)$  and transform of the adjustment window is  $\mathbf{W}_k(v)\neq 1$ . That is why the discrete Fourier transform of the fragment of the signal improved by the adjustment window, beside the harmonic components of the signal and substitute spectrums also includes the components contained in the window function. This results in an additional inaccuracy of the information contained in the discrete spectrum.

The distortions of the discrete Fourier spectrum of the retrieved fragment of the signal that come from the substitute spectrums can be reduced by extending of the retrieval time. It is known that for constant bandwidth  $[0,v_{Nyq})$  as the retrieval time *T* grows the size of the set of admissible frequencies increases and the distance between them decreases. The number of the signal components that are probable to find their place in the set of admissible frequencies grows. As a result, the amount of information that can be accurately conveyed in the discrete spectrum increases. Also increases the number of the components of the substitute spectrums recovering the components of the signal of frequencies that do not belong to this set, which results in a better accuracy of the recovery.

For  $T \rightarrow \infty$  frequency  $v_T \rightarrow 0$  the admissible frequency set becomes infinitely large and the discrete spectrum approaches a continuous form. A practical realization of such a case is impossible due to an infinite length of the retrieval time. Even if that were possible, the determination of a discrete spectrum of an infinitely dense set of admissible frequencies would not eliminate the distortions.

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### TRANSFORMACJA FOURIERA – WAŻNE NARZĘDZIE W DIAGNOSTYCE WIBROAKUSTYCZNEJ

Streszczenie. Mierzalne wielkości fizyczne, charakteryzujące procesy towarzyszące funkcjonowaniu urządzenia mechanicznego, mogą być wykorzystane jako sygnały niosące zakodowane informacje. Aby je odczytać sygnał należy pobrać i obrobić. Obróbka polega najczęściej na transformacji sygnału do dziedziny częstotliwości metodą DFT. Wykorzystanie takiej obróbki wymaga wiedzy jak informacja diagnostyczna jest wytwarzana w dyskretnej charakterystyce sygnału. W tym celu należy badać model, który odzwierciedla pobranie sygnału w skończonym przedziale czasu, jego przetwarzanie A/C i periodyzację. Badania wykazują, że procedura DFT wytwarza prążki reprezentujące składowe harmoniczne sygnału tylko dla częstotliwości nv, które są całkowitą krotnością odwrotności czasu pobrania. Składowe o innych częstotliwościach są przedstawiane w postaci widm zastępczych. W konsekwencji, widma dyskretne są rezultatem superpozycji fal o częstotliwościach należących do zbioru dopuszczalnych i widma zastępczych reprezentujących fale, które do tego zbioru nie należą.

Słowa kluczowe: diagnostyka wibroakustyczna, numeryczna obróbka sygnałów transformacja Fouriera.

# Energy efficiency analysis of flat and vacuum solar collector systems

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S u m m a r y. This paper presents the findings of analyses depicting changes in solar radiation conversion efficiency in flat and vacuum solar collectors. It also sets out the efficiency for the entire system based on a 24-hour cycle. On the basis of results models have been found which define these efficiencies through experience (storage tank fluid capacity, surrounding temperature and total solar radiation). This model has also been validated and confirmed as useful for estimating efficiency and therefore, for selecting surfaces of the analyzed types of collectors in systems using these kinds of devices. Concerning the approved conditions the time required for the reimbursement of investment costs has also been defined.

Key words: flat and vacuum solar collectors, conversion efficiency, solar radiation

# 1. INTRODUCTION

The growing cost of energy, fear associated with the possibility of exhaustion of fossil energy sources, the need to increase the security of fuel and energy supply and concern for environmental protection have led to rapid growth of interest in the use of renewable energy. Solar radiation energy, which is converted into heat in flat and vacuum solar collectors, is being used more and more often as a component of renewable energy resources.

Of its many possible applications, heat obtained from solar collectors is also used in horticultural production, primarily for: supplementing the heating of structures under cover [Kurpaska et al 2004, Vox et al 2007], supplementary or basic heating of plastic tunnel bedding with the purpose of accelerating crop growth, preparation of processing water for the watering of plants, preparation of seedlings for planting, heating requirements for the post-harvest preparation of fruit and vegetables and heat treatment of soil pathogens [Al-Karaghouli and Al-Kayssi 2010]. A number of research centres has analysed in detail matters relating to the conversion of radiation for various configurations and conversion system equipment.

Adsten et al [2002] analysed the impact of solar collector locations (both flat and vacuum) in northern Europe for operating effectiveness. The impact of annual energy was determined and it was confirmed that the amount of obtained energy is closely related to surrounding climate conditions. Apart from research on the use of individual collectors for energy purposes, specialist literature also provides the findings of research focusing on the coupling of collectors with heat pumps (so-called bivalent or hybrid systems). Hawlader et al [2001] researched the energy effects of the system in which the heat pump was coupled with the solar collector. The researchers defined the Coefficients of Performance for given system constituents. They also defined the rate of return on financial outlay and the COP for the entire system. Kjellsson et al [2010] carried out an analysis of the use of renewable energy for a residential building, provided by solar collectors corresponding with a heat pump. They concluded that it was necessary to optimise system components because the configuration of the system and the dimensions of its components depend on local environmental conditions. Eisenmann et al [2004] analysed the possibility of saving materials in the production of collectors and, amongst other things, replacing them with other more available materials. Following research and the optimisation of collector construction, the above researchers noted a possible reduction of 25% in traditional material without negatively impacting the effectiveness of converting solar radiation energy into heat. Aye et al [2002] studied the use of a compressor heat pump coupled with solar collectors for the purpose of heating processing water in residential buildings. In their analysis they compared aspects of energy and cost-effectiveness of the system under consideration in relation to separate constituent parts and indicated the conditions for which the proposed solution may be used in other facilities. Sozen et al [2008] used neural networks for the purpose of analysing the

work effectiveness of flat solar collectors; they used the following as input values: collector surface temperature, solar radiation intensity and duration, angle of declination, azimuth angle and inclination angle. In their summary they indicated their usefulness of the elaborated network architecture. Trillat-Berdal et al [2007] analysed the use of a heat pump coupled with solar collectors for the purpose of heating residential buildings. This system guaranteed the channelling of heated water (following the meeting of given conditions) through collectors to a buffer tank in which lower heat source exchangers were located. Heat exchanger performance and general system operating effectiveness were defined. They also analysed heat pump operation in which the lower heat source was the intake of geothermal water and solar collectors. When using the existing numeric model they defined the operating parameters of the system under consideration and presented the energy and economic effects and the quantity findings of reducing the emission of harmful substances into the atmosphere. Kaygusuz [1995] presented the findings of theoretical and experimental analysis of the heating system in which a heat pump (used for heating purposes) was coupled with solar collectors. The model took into account given system components, whilst experimental research demonstrated satisfactory comparison. The model permits the calculation of collector surface, their efficiency and heating medium temperature. Badescu [2002] presented the findings of theoretical analysis in which he considered two systems used for the heating of buildings, namely the hybrid system (solar collectors coupled with the heat pump) and the single system in which only the heat pump was used for heating the building. The coefficient of performance of the heat pump was defined and it was concluded that the hybrid system is more useful for the heating of facilities. Fuller [2007] carried out a theoretical analysis and performed an experimental verification of the system in which use was made of water heated up in solar collectors for the heating of plastic tunnels. The water was collected in a storage tank and from there channelled (in a closed system) for the washing of the surface covering the facility. The energy effects of the system were defined and its usefulness in areas of high radiation was indicated.

Generalizing the results of research one may also state that the effectiveness of conversion depends not only on system configuration but also on the parameters of the surrounding climate.

The main purpose of research involved analysis of the effectiveness of conversion.

#### 2. MATERIAL AND METHODS

#### 2.1. EXPERIMENT SET-UP

Tests were conducted with the use of laboratory facilities located at the Agricultural University in Krakow (Figure 1).



Fig. 1. Scheme of the laboratory stand

As indicated the laboratory facility comprises flat (7.8m<sup>2</sup> effective surface) and vacuum (surface of 4.3m<sup>2</sup>) solar collectors. The circulating medium flowed through a coil located in the buffer tank, which resulted in higher temperature of the water in the tank. Heat reception from the tank (1) was attained thanks to heat pump operation (2), in which the lower source constituted an additional heat exchanger located in the buffer tank. Heat was supplied to the plastic tunnel heating system (4) from the buffer tank (3). During the performance of the experiments, whose purpose was to analyse the effectiveness of collector operation, one of the collector types (liquid or vacuum) did not participate in the conversion of solar radiation.

During research the following was used for measuring the analysed values: the liquid stream flowing through the impulse flow meter (5), water (inside container, circulating liquid) and air temperature measured with the use of copper-constantan thermocouples (6) and solar irradiation by pyranometer (7).

All values were monitored and archived during sampling every 30 seconds with the use of the computer measurement system (CMS).

#### 2.2. ANALYSIS

System efficiency analysis may be may be considered as instantaneous efficiency (depending on  $d\tau$  sampling time and long-term efficiency.

• Instantaneous efficiency of solar collectors Heat obtained from the collector during  $d\tau$  is equal to:

$$Q(\Delta \tau) = \dot{m} \cdot c_w \cdot (T_z - T_p) d\tau, \quad \mathbf{J}$$
(1)

In turn, conversion efficiency according to the standard expressed in the relationship between heat from the conversion and the sum of solar radiation energy, in other words:

1

$$\gamma = \frac{Q(\Delta \tau)}{\Sigma R_{zewn} \cdot F_k \cdot d\tau}$$
(2)
where:  $\dot{m}$  - stream of circulating medium mass, kg×s<sup>-1</sup>; c<sub>w</sub>- medium specific heat, J×kg<sup>-1</sup>×K<sup>-1</sup>; T<sub>z</sub>, T<sub>p</sub>- respective feed temperature (T<sub>z</sub>) and return (T<sub>p</sub>) of the circulating medium;  $\sum R_{zew}$  - sum of solar radiation, W×h; Fk- surface of tested collectors, respectively 4.3 m<sup>2</sup> (vacuum) and 7.8 m<sup>2</sup> (liquid collector).

## • Long-term efficiency

In the considered system this efficiency expresses the relationship between the quantity of energy stored in the storage tank i.e. the difference between useful collector heat and total heat loss from the tank into the environment and the sum of solar radiation energy which reaches the collectors. In consideration of the above this dependency is expressed as follows:

$$\eta_{med} = \frac{\int_{h_{E}}^{h_{W}} Q(\tau) d\tau - A_{S} U_{S} \int_{day} \left[ T_{S}(\tau) - T_{ot}(\tau) \right] d\tau}{F_{k} \int_{h_{E}}^{h_{W}} R_{zew}(\tau) d\tau}$$
(3)

where:  $h_E$ ,  $h_W$ - time of solar radiation penetration on the collector,  $A_S$ - surface heat loss of the storage tank,  $m^2$ ; Us- replacement ratio of heat loss from the tank, W m<sup>-2</sup> K<sup>-1</sup>;  $T_S$ - instantaneous temperature of the liquid in the tank, °C;  $T_{ot}$ - tank surrounding temperature, °C,  $\tau$ - time, s.



**Fig. 2.** Storage tank with coil:  $A_w$ - coil surface, m<sup>2</sup>;  $U_w$ - ratio of heat penetration from the coil to water, W m<sup>-2</sup> K<sup>-1</sup>; T<sub>1</sub>, T<sub>2</sub>- tank liquid temperature, °C; m<sub>w</sub>- stream of circulating medium flowing through the coil, kg s<sup>-1</sup>.

For the purpose of the analysis a period of time equal to 24 hours was approved as the long-term storage period.

In the presented dependency a difficulty arises in indicating the penetration ratio of tank heat into the atmosphere ( $U_s$ ). The diagram of this system is indicated graphically in Figure 2.

The following method was used for the purpose of designating the  $U_s$  coefficient. The tank is an exchanger in which there is liquid of a given mass (m) and specific heat (c<sub>p</sub>). Water is heated in the tank following the transfer of heat from the medium which flows through the coil. There is thermal stratification in the tank, as a result of which a vertical temperature gradient takes place (t<sub>1</sub> and t<sub>2</sub> water temperature). In order to introduce the dependency defining change of tank water temperature, taking into account heat loss (Qstr), use has been made of standard heat balance. The dependency on indicating the U<sub>s</sub> coefficient in *dt* differential time was designated as follows (4):

$$U_{s} = \frac{m \cdot c_{p} \cdot (T_{0} - T_{\Delta \tau})}{A_{s} \cdot (T_{avg} - T_{ot}) d\tau}$$
(4)

where,  $T_{avg}$ - is average liquid temperature at the beginning and at the end of the d $\tau$  interval, °C;  $T_0$ ,  $T_{\Delta \tau}$ - is liquid temperature at the beginning ( $T_0$ ) and at the end of the interval ( $T_{\Delta \tau}$ ), °C.

On the basis of findings a model dependency was established between efficiency defined through measurement and efficiency designated from the model. In order to define the differences application was made of relative differences and mean square error calculated from the dependence:

$$\sigma = \left(\sum_{i=1}^{n} \frac{\left(\eta_{calc} - \eta_{mod}\right)^2}{n}\right)^{0.5}$$
(5)

where:  $\eta_{calc}$ ,  $\eta_{mod}$ - calculated ( $\eta_{calc}$ ) and designated efficiency ( $\eta_{mod}$ ) from the proposed model, n- number of comparisons.



Fig. 3. Heat quantity generated in a solar vacuum collector in terms of total solar radiation.



Fig. 4. Heat quantity generated in a flat vacuum collector in terms of total solar radiation.

#### 3. RESULTS AND DISCUSSION

Tests were carried out on varying volumes of water in the tank, between  $1.25 \text{ m}^3$  and  $1.78 \text{ m}^3$  (vacuum collectors) and between  $2.22 \text{ m}^3$  and  $3.75 \text{m}^3$  for flat collectors. The quantity of test liquid for flat collectors was respectively: 2.22 m<sup>3</sup>, 2.58 m<sup>3</sup>, 2.9 m<sup>3</sup> and 3.22 m<sup>3</sup>; and for vacuum collectors:  $1.25 \text{ m}^3$ ,  $1.4 \text{ m}^3$ ,  $1.6 \text{ m}^3$  and  $1.78 \text{ m}^3$ . Figures 3, 4 and 5 present examples of measured amounts.

The dependency, which arose as a result of solar radiation conversion, between the quantity of heat generated in the collectors (in relation to unit surface) in terms of total solar radiation energy, is depicted in Figures 3 and 4, respectively for vacuum collectors (Figure 3) and flat collectors (Figure 4).

Under test conditions the scope of heat quantity change spanned between 0.2 to  $364.2 \text{ kJ}\times\text{m}^{-2}$ , (vacuum collectors), and between 2.6 to almost 280 kJ/m<sup>2</sup> for flat collectors. In turn, average quantities of obtained heat stood at 130 kJ×m<sup>-2</sup>, (vacuum collectors), and 103 kJ×m<sup>-2</sup> (flat collectors). Taking into account the above data it

stems that from the unit surface of a vacuum collector (based on average values) almost 18% more heat is obtained in comparison to flat collectors. This analysis was carried out for similar surrounding conditions (the sum of solar radiation energy, surrounding temperature).

Assuming the futility of providing all possible approaches, Figures 5 and 6 illustrate the impact of surrounding temperature and the sum of solar radiation on the change of effectiveness of the conversion of radiation for flat collectors. Calculations were performed in relation to the unit surface of flat collectors (Figure 5) and for storage tank fluid capacity at 2.25 m<sup>3</sup>. The same course of change of effectiveness for vacuum collectors (for tank capacity equivalent to 1.25 m<sup>3</sup>) is presented in Figure 6.

For maximum liquid volumes applied in the buffer tank (flat collectors, 3.22m<sup>3</sup> and vacuum collectors, 1.78m<sup>3</sup>) the obtained calculations have been presented graphically in Figures 7 and 8.

In analyzing the obtained values one may state unequivocally that conversion effectiveness grows together with the growth of the sum of solar radiation and sur-



**Fig. 5.** Impact of surrounding temperature and the sum of solar radiation on the effectiveness of radiation conversion for flat collectors (liquid volume equivalent to 2.25m<sup>3</sup>).



**Fig. 6.** Impact of surrounding temperature and the sum of solar radiation on the effectiveness of radiation conversion for vacuum collectors (liquid volume equivalent to 1.25m<sup>3</sup>).



**Fig. 7.** Impact of surrounding temperature and the sum of solar radiation on the effectiveness of radiation conversion for flat collectors (liquid volume equivalent to  $3.22m^3$ ).



**Fig. 8.** Impact of surrounding temperature and the sum of solar radiation on the effectiveness of radiation conversion for vacuum collectors (liquid volume equivalent to 1.78m<sup>3</sup>).

rounding temperature. Under test conditions, the average efficiency value for tested collectors kept changing depending on liquid volume in the storage tank for: vacuum collectors - from 0.46 to 0.72 (respectively for tank capacity of 1.25 and 1.78 m<sup>3</sup>), and ion the case of flat collectors from 0.4 (tank capacity of 2.25m<sup>3</sup>) to 0.6 (for capacity of  $3.22m^3$ ). On the basis of obtained data it stems unequivocally that in order to obtain the highest level of efficiency through a solar collector system it is necessary to apply the above indicated liquid volumes in storage tanks. It was also noted that under the same conditions (for vacuum collectors almost 900 measure cycles were performed and 840 cycles for flat collectors), conversion effectiveness for vacuum collectors is on average 18% higher than in the case of flat collectors. The increase in conversion effectiveness as a positive function of temperature increase and the sum of solar radiation is the outcome of the growth in direct radiation share and reduced heat losses from the collector casing into the surroundings.

Following the performance of a series of tests, using non-linear estimation by means of the quasi-Newton method whilst retaining rates of convergence at 0.001, a dependence was found between independent variables (liquid volume in the tank -  $V_{zb}$ , surrounding temperature -  $t_{ot}$  and the sum of solar radiation energy -  $R_{sl}$ ). This connection for vacuum collectors is defined by the following dependence:

$$\eta = -0.5 \cdot V_{zb} + 1.24 \cdot t_{ot}^{0.023} + 3.85 \cdot 10^{-5} \cdot \sum R_{sl}^{1,19}; \quad R^2 = 0.87$$

for the scope of application:  $1.25 \le V_{zb} \le 1.78 \text{ m}^3$ ;  $10.3 \le t_{ot} \le 37.5^{\circ}\text{C}$ ; 1.78;  $15.2 \le R_{sl} \le 525 \text{ Wh}$ 

In turn, for flat collectors this connection is expressed as follows:

$$\eta = -0.22 \cdot V_{zb} + 0.52 \cdot t_{ot}^{0.162} + 0.0168 \cdot \sum R_{sl}^{0.448}; \quad \mathrm{R}^2 = 0.82$$

for the scope application:  $2.25 \le V_{zb} \le 3.22 \text{ m}^3$ ;  $10.3 \le t_{ot} \le 37.5^{\circ}\text{C}$ ; 1.78;  $15.2 \le R_{sl} \le 525 \text{ Wh}$ 

These forms of dependence were selected on the basis of the largest coefficient of determination. In order to compare measured and calculated efficiency according to the proposed dependencies, in Figures 9 and 10 a global comparison between these values has been presented (for vacuum collectors Figures 9 and Figures 10 and for flat collectors).

Calculated heat penetration coefficient form the tank to the surroundings (from model 4) stood at 2.4 W/m<sup>2</sup>K. This illustrates unsatisfactory storage tank insulation.

Assuming the futility of providing all possible approaches, it has been decided to present in Figure 11 sample changes of long-term efficiency ( $\Box_{med}$ ) calculated from the model (3) in terms of independent variables (surrounding temperature and sum of solar radiation). These dependencies are obtained for flat collectors and water volume in tanks equivalent to 2.22m<sup>3</sup>. Under the test conditions this efficiency changes from 0.21 to 0.52. When analysing all combinations (type of collector, tank liquid volume), this scope ranges between 0.18 to 0.52 (flat collectors) and from 0.23 to 0.61 (vacuum collectors). Smaller values were obtained for larger liquid capacity in the storage tank.

Changes in analysed efficiency are the outcome of reduction in temperature differences (collector temperature, tank temperature – surrounding temperature) and the larger share of direct radiation. The greater the values of these independent variables the smaller the heat loss from the collector, the storage tank and the more efficient conversion of direct radiation.

Summing up the research findings one may state that, apart from their cognitive values (defined under operating conditions), could also be applied. This stems from the fact that in each designed system which stems from its specifics, it is necessary to have an understanding of the efficiency of converting solar radiation into heat. The analysis also shows that vacuum collectors are more effective in converting radiation into useful heat. Conversion efficiency obtained through research demonstrates somewhat lower values than the parameters indicated by the producers of this equipment. However, the difference in the operating effectiveness of flat and vacuum collectors (higher efficiency) analyzed during



Fig. 9. Comparison between efficiency calculated from the proposed model and efficiency designated from vacuum collector tests.



Fig. 10. Comparison between efficiency calculated from the proposed model and efficiency designated from flat collector tests.



Fig. 11. Long-term efficiency  $(\square_{med})$  concerning surrounding temperature and sum of solar radiation energy.

the summer (May - September) depended primarily on the surrounding temperature and solar radiation.

Of course, the attractiveness of the solution and the recommendation of a given type of collector depend on financial analysis. For this reason, in order to illustrate this topic, a calculation was made of payback on financial investment. The analysis took into account the following: The cost of purchasing the installation in entirety (vacuum or flat collectors included), average quantity of solar radiation (according to latitude of 54°), installation operating time and cost of electricity. For calculation purposes, tank capacity corresponding to maximum collector efficiency and total respective solar collector surface (4 flat collectors) of 7.8 m<sup>2</sup> and 4.3m<sup>2</sup> (flat collectors). Analysis findings, assuming that a flat collector set costs PLN 9,000 and a vacuum collector set costs PLN 12,000, indicate that return on investment would be 6.7 years and 6.5 years respectively.

#### 4. CONCLUSIONS

The following conclusions are based on the above analysis:

- 1. Depending on storage tank liquid volume solar radiation conversion efficiency is between 0.46 and 0.72 for vacuum collectors and between 0.4 and 0.6 for flat collectors.
- 2. Under comparable experimental conditions, conversion efficiency for vacuum collectors is on average 18% higher than in the case of flat collectors.
- 3. The model defining the efficiency of solar radiation conversion in vacuum collectors is expressed as follows:

$$\eta = -0.5 \cdot V_{zb} + 1.24 \cdot t_{ot}^{0.023} + 3.85 \cdot 10^{-5} \cdot \sum R_{sl}^{1,19}; \quad \mathbf{R}^2 = 0.87$$

for the scope of application:  $1.25 \le V_{zb} \le 1.78$  m<sup>3</sup>;  $10.3 \le t_{ot} \le 37.5$ °C; 1.78;  $15.2 \le R_{sl} \le 525$  Wh

for flat collectors:

$$\eta = -0.22 \cdot V_{zb} + 0.52 \cdot t_{ot}^{0.162} + 0.0168 \cdot \sum R_{sl}^{0.448}; \quad \mathbf{R}^2 = 0.82$$

for the scope of application:  $2.25 \le V_{zb} \le 3.22 \text{ m}^3$ ;  $10.3 \le t_{ot} \le 37.5^{\circ}\text{C}$ ; 1.78;  $15.2 \le R_{sl} \le 525 \text{ Wh}$ 

- 4. Depending on the type of collector and liquid capacity in the storage tank, the daily efficiency of the analysed conversion system is between 0.18 and 0.61.
- 5. The payback period on financial investment in a solar radiation conversion system depending on the type of collector is respectively as follows: 6.5 years for vacuum collectors and 6.7 years for flat collectors.

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# ANALIZA EFEKTYWNOŚCI ENERGETYCZNEJ PŁASKICH I PODCIŚNIENIOWYCH UKŁADÓW KOLEKTORA SŁONECZNEGO

S tr e s z c z e n i e. W artykule przedstawiono wyniki analiz obrazujących zmiany sprawności konwersji promieniowania słonecznego w płaskich i próżniowych kolektorach słonecznych. Określono również wydajność całego systemu opartego na cyklu 24-godzinnym. Na podstawie wyników zostały znalezione modele, które eksperymentalnie określają te efektywność (zbiornik pojemność płynu, temperatura otoczenia i całkowite promieniowanie słoneczne. Modele te zostały również zatwierdzone i potwierdzone jako przydatne do oszacowania wydajności, a zatem przy wyborze powierzchni analizowanych typów kolektorów w systemach korzystających z tego rodzaju urządzeń. Określono również czas potrzebny na zwrot kosztów inwestycji.

Słowa kluczowe: płaskie i próżniowe kolektory słoneczne, wydajność konwersji, promieniowanie słoneczne.

# Energy efficiency of ground heat exchangers co-operating with a compressor heat pump

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S u m m a r y. The work presents results of an analysis of the coefficient of performance of a heat pump co-operating with ground heat exchangers. Three types of exchangers were examined: horizontal, vertical- made at the depth of 20 m (type I) and at the depth of 100 m (type II). It was proved that the highest value of the coefficient of performance (the COP) occurs for vertical exchangers (type I), slightly lower for horizontal exchangers and the lowest for vertical exchangers (type II). The statistical analysis, which was carried out, proved that the type of an exchanger significantly influences the value of the coefficient of performance; its average values are also statistically significant. Significance of the influence of temperature inside a facility on the value of the coefficient of performance was not proved.

Key words: compressor heat pump, vertical, horizontal ground heat exchanger

#### INTRODUCTION

Constant search for methods of reducing energy outlays and alternative and more effective heat sources in technological processes and heating of facilities results from increased costs of obtaining heat from traditional carriers and from the care for the natural environment. Such activities are also influenced by policy of the European Community countries, which stimulates the use of renewable sources of energy. One of the methods of realization of this purpose is a heat pump, which cooperates with ground heat exchangers. Issues concerning the analysis of the effectiveness of the system, in which heat pumps are used, were the subject of the research in many scientific centres. Thus, Wood et al. (2010) analysed operation effectiveness of the heat pump co-operating with vertical ground heat exchangers located in vertical poles, which constitute a foundation of housing estates. As a result of the research which they carried out, they determined usefulness of such a construction, they calculated a temporal and seasonal coefficient of energy efficiency of the system (calculated by means of the relation of the obtained thermal power with the supplied electric power). Kim et al. (2011) presented a work containing results of the researched compressor heat pumps varied according to thermal efficiency and the applied thermaldynamic factor. Air, water and soil were used as a lower heat source. In the constructed models, they included particular cycles of thermal-dynamic transformation of the circulation factor. On the basis of the tests which they carried out, they determined a percentage share of particular electric energy receivers (a compressor, a circulating pump) in shaping the value of the coefficient of energy efficiency of the system. Congedo et al. (2012) using the CFD technology analysed the thermal issues in the ground, in which the ground heat exchangers cooperating with the heat pump were installed. As a result of the simulation which was carried out, influence of depth, ground conductivity and the flow speed of the circulation factor on the amount of heat obtained by the exchangers located in a flat and loop arrangement were determined. Temperature of ground at random depth and in random time was described by an equation of heat conductivity at the assumed periodical change of temperature of its outer layer. It was found that from among the analysed independent variables moisture of the ground influences the amount of the obtained heat the most, whereas from among the researched geometrical arrangements the loop system is recommended. Yang et al. (2010) carried out a review of models used for describing phenomena occurring in the ground with the vertical heat exchangers. They concluded that there is a need to verify these models and the issues related to underwater flow which influence a change of central temperature should be added. Florides and Kalogirous (2007) presented construction solutions of the ground heat exchangers and they characterised mathematical models used to describe phenomena in the ground. As a result of the analysis which they carried out,

they stated that thermal-physical properties of the ground centre influences the amount of the heat taken up by the ground exchangers whereas, span and spatial sitting of exchangers and thermal conductivity of the ground are decisive factors in the vertical exchanger. Partenay et al. (2011) worked out a mathematical model of phenomena, which take place in the flowing circulation factor in the vertical ground exchangers. The compiled model was resolved with a numeric method (of definite elements) while a change of ground temperature during operation of the heat pump was the analysed issue. On the basis of the experimental tests which were carried out (a system of six vertical heat exchangers), correctness of this model was reported and a relation of the heat pump operation efficiency to temperature in the heat exchangers of the system (a steamer, a condenser) were found. Lee and Lam (2008) carried out a computer simulation for the system composed of vertical exchangers co-operating with the heat pump. In the isolated space of the ground, relations of heat exchange with loops of particular meshes were worked out (with the method of definite differences). As a result of the analysis, they determined a periodical variability of the ground temperature as well as the value of the coefficient of heat transfer for the ground heat exchangers. Trillat et al. (2006) presented results of experimental research in which the heat pump cooperated with solar collectors forming the so-called hybrid system. Energy effects of such a system along with its energy efficiency (the coefficient of performance) and calorific effect of the ground exchangers were determined whereas the authors recommended the considered system for heating facilities. On the basis of a long-term research, Huang and Lee (2004) determined the consumption of electric energy used for driving a heat pump. Calculations were carried out in relation to a unitary growth of temperature of liquid stored in the buffer tanks of the heat pump. Ozgener and Hepbasli (2005a) analysed energy issues and financial outlays incurred on the use of the heat pump (co-operating with the vertical ground heat exchangers) for heating purposes. The authors worked out a simulation model, which may be used for an analysis of financial inputs at using the heat pump for heating facilities. Ozgener and Hepbasli (2005b) presented results of experimental research on using a heat pump for heating a greenhouse. They described thermal efficiency of vertical ground heat exchangers and temperature of air inside a greenhouse at supplying heat only from a heat pump. They also determined values of the coefficient of work efficiency of the system divided into days of various weather conditions. Ozgener and Hepbasli (2005c) in the experimental research determined the work efficiency of the heat pump with the vertical heat exchangers used for heating a greenhouse. Moreover, they determined a value of the coefficient of work efficiency of the system (the COP), which they related with total energy supplied from the heat pump and to this part of energy, which was used for heating purposes of the above assumed temperature inside a greenhouse. Kurpaska's work (2008) presents nomograms for determining construction and operation parameters in which the heat pump was working in a monovalent and hybrid system. The monovalent system constituted a co-operation of the heat pump with the grounded exchangers (both horizontal and vertical) whereas in the hybrid system a cumulative tank in which collected water was heated with solar collectors was the lower source of the pump.

The presented review of the literature explicitly results in actual analysis of the research issue, as the use of the heat pump in heating installations of facilities is one of future technical solutions. It is a consequence of the fact that the heat pump co-operating with a cogenerative system (joint generation of heat and electric energy) is an ideal receiver of electric energy generated in this system. However, the system of obtaining heat from the bottom source, next to a type of the used pump decides on efficiency of using electric energy. Analysis of these issues is a main purpose of the presented work.

#### MATERIAL AND METHODS

Energy efficiency of the system the heat pump cooperating with the system of heat consumption and reception) decides on its economic cost-effectiveness.

Thus, this issue was analysed for a laboratory stand constructed in facilities of the Department of Production Engineering and Power Industry of the University of Agriculture in Kraków.

This stand (fig. 1) is composed of: a compressor heat pump, vertical ground exchangers: depth approx. 20 m (two U type exchangers and 2x U), depth 100 m (one U type exchanger and the other 2U type, horizontal exchangers in a geometric system: a single loop, a double loop and spiral arrangement. Two heat-air exchangers mounted in a laboratory foil tunnel constituted the system of heat reception.



impulse flow meter; •PT1000 resistance sensors; 1- heat pump;
 2- buffer tank

Fig. 1. Scheme of the laboratory stand

During the experiments, necessary measurement amounts were monitored and recorded using an original Computer Measurement System. A stream of the flowing



Fig. 2. Temporary course of some measured parameters in the expriment

factor was measured with an impulse flowmeter, while temperature (of supply and return of the circulation factor) in particular exchangers as well as air temperature (outside  $t_{out}$  and inside a facility  $t_{ins}$ ) with a resistance sensor PT1000. Additionally, during the research, a demand for electric power used for driving elements of the researched system (a compressor, a circulating pump and circulation pumps of exchangers of the upper heat source) was determined and radiation intensity Rs was measured (with a pyranometer).

Using a definition of the heat pump operation, an equation of energy balance (including amount of heat obtained in a condenser of the analysed pump - Q) may by written down in the following form:

$$Q = W_{PC} + Q_{GZ} \tag{1}$$

Operation efficiency of the heat pump in the system may be described with the coefficient of performance (coefficient of energy efficiency), which was defined pursuant to the standard PN-EN 255 in the following form:

$$COP_{grz} = \frac{Q_{GZ} + W_{PC}}{W_{PC}} = 1 + \frac{Q_{GZ}}{W_{PC}}$$
 (2)

In a differentiable time  $d\tau$ , parameters necessary to describe the amount of heat obtained by the analysed ground heat exchangers, electric energy consumption  $(W_{PC})$  and amount of heat obtained by exchangers located in the heated facility  $(Q_{GZ})$  were measured.

Moreover, in the said time  $d\tau$  the amount of heat obtained by the analysed ground exchangers was determined in relation to:

$$Q_{DZ} = \sum_{i=1}^{9} \left( \sum_{i=1}^{n} m_{cDZ,i} \cdot c_{c} \cdot \left( T_{z-DZ,i} - T_{p-DZ,i} \right) \right) d\tau_{PC}$$
(3)

where as for the system of heat reception in analogical time this relation takes the following form:

$$Q_{GZ} = \sum_{i=1}^{2} \left( \sum_{i=1}^{n} m_{cGZ,i} \cdot c_{p} \cdot \left( T_{z-GZ,i} - T_{p-GZ,i} \right) \right) d\tau_{PC+GZ}$$
(4)

where:  $Q_{GZ}$  heat supplied to the inside of the facility [J];  $Q_{DZ}$  – heat obtained form the outside of the ground [J];  $W_{PC}$  – electric power obtained by elements of the

system [W];  $\tau_{pC}$ ,  $\tau_{GZ}$  – operation time of the heat pump  $(\tau_{pC})$  and of the upper source $(\tau_{GZ})$  [s];  $m_c$  – stream of the lower circulation factor  $(m_{cDZ})$  and of the upper  $(m_{cGZ})$  source [kg·s<sup>-1</sup>],  $c_c$  – specific heat of the circulation factor [J·kg<sup>-1</sup>·K<sup>-1</sup>],  $T_{z-DZ}$  and  $T_{p-DZ}$  – temperature of supply and return of the circulation factor of the lower heat source,  $T_{z-GZ}$  and  $T_{p-GZ}$  – temperature of supply and return of the circulation factor of the source [°C].

#### RESULTS AND A DISCUSSION

The research was carried out in 2012. Fig. 2 presents an exemplary course of some measured values. Assuming pointlessness of all possible courses, visualisations of the measured parameters were limited to parameters of the liquid -air exchangers, which constitute an upper heat source in a tunnel, temperature inside and outside of the facility, difference between temperature of supply and return of the circulation factor and the state of work of the heat pump. Selected symbols include:

 $\rm T_{z\text{-}D21}, \rm T_{z\text{-}D22}$  – difference in temperature of the circulation factor,  $\rm R_s$  – intensity of solar radiation outside the facility;  $\rm V_{D21}, \rm V_{D22}$  – indications of a water meter presenting amount of the factor flowing through exchangers supplying heat to the inside of the facility:  $\rm t_{ins}, \rm t_{out}$  – respectively temperature inside and outside the facility, HP – operation state of the heat pump (value above zero means operation state of the heat pump).

According to what has been presented, in the period of 48 hours, the heat pump was working through 37 cycles of operation of the length within 11.5 to 32 minutes. Within this time, for driving technical devices of the system (a pump compressor, circulation pumps) almost 86 kWh of electric energy were used and 85.4 kWh of this amount was used for driving elements of the heat pump (a compressor, a circulating pump) whereas, approx. 0.6 kWh were used for circulation pumps obtaining heat from a buffer tank of the pump. In the presented period of time 460 MJ of heat where delivered to the facility.

Almost 500 cycles of pump operation were analysed (for all conditions of the experiment). For every cycle from the equation (2) a coefficient of performance was calculated.

Fig. 3 and 5 presents a calculated coefficient of operation efficiency of the pump co-operating with the analysed ground heat exchangers. Type I of vertical ground heat exchangers means exchangers located at the depth of 18 m while the type II means ground exchangers of 100 m depth.

When analysing the obtained courses, one may notice that the highest average value of the coefficient COP (the COP = 2.69) was obtained for the case when the heat pump was co-operating with the vertical ground exchangers located at 100 m depth. Whereas, when the pump co-operates with the horizontal exchangers, an average value of COP was 2.53, while for the vertical exchangers of approx. 20 m depth, the COP was 2.42. Comparable values of the surrounding climate were selected for the analysis. Thus, vertical exchangers made at the depth of 100 m are recommended as the lower heat source of the pump.

While analysing these relations, one may find that the co-operation of the heat pump with the vertical exchangers of 100 m depth is characterised also by a lower variability of the value of the coefficient of performance.



Fig. 3. Course of changes in energy efficiency of the heat pump co-operating with horizontal exchangers.



Fig. 4. Course of changes in energy efficiency of the heat pump co-operating with vertical ground exchangers of approx. 20 m depth.



Fig. 5. Course of changes in energy efficiency of the heat pump co-operating with ground vertical exchangers at 100 m depth.

For the obtained data, at the level of significance  $\Box$ =0.05 a statistical analysis was carried out using the Statistica<sup>®</sup> packet. Fig. 6 presents results of average values along with a standard deviation of analysis.



Fig. 6. Results of average values of the coefficient of performance with a standard deviation

The analysis of variance in a single classification, which was carried out proves that the assumed factors of the experiment (a type of the ground exchanger) significantly influence the analysed value of the coefficient of performance. Whereas, Duncan test proved that the average values of this coefficient differ in a statistically significant way.

Fig. 6 presents a graphic relation of the coefficient of efficiency of the heat pump (calculated from the equation 2) and temperature inside the facility.

One may notice that growth of temperature inside a foil tunnel means a slight decrease of the coefficient of efficiency of the heat pump. The statistical analysis did not prove significance of the regression coefficient. It means that there is no linear influence of temperature inside a foil tunnel on the value of the COP. Moreover, the value of the coefficient of determination ( $R^2$ =0.18) does not prove statistically significant relation of the COP with temperature inside a facility. It results from the relation of intensity of heat reception between exchangers and a surrounding air, since the higher temperature is around the heat exchangers, the lower value of the transfer coefficient gets. At the low difference of temperatures, the operation time of circulating pumps from the system of heat reception increases. However, the power used for driving circulating pumps is many times lower than a demand for power by a compressor and a circulating pump of the lower heat source.

# CONCLUSIONS

The highest average value of the COP was obtained for the vertical ground heat exchangers (type II), slightly lower for the horizontal exchangers and the lowest for vertical exchangers (type I). The analysis of variance proved that the assumed factors of the experiment (a type of the ground exchanger) considerably influence the analysed value of the COP and average values of this coefficient differ in a statistically significant way. Along with a temperature growth inside a foil tunnel, the value of the COP decreases slightly. However, the coefficient of regression is not statistically significant.

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Fig. 7. Dependence of the heating efficiency coefficient on the temperature inside the object

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# EFEKTYWNOŚĆ ENERGETYCZNA WYMIENNIKÓW GRUNTOWYCH WSPÓŁPRACUJĄCYCH ZE SPRĘŻARKOWĄ POMPĄ CIEPŁA

Streszczenie. W pracy przedstawiono wyniki analizy wartości współczynnika efektywności pracy sprężarkowej pompy ciepła współpracującej z wymiennikami gruntowymi. Badano trzy typy wymienników: poziome, pionowe- wykonane na głębokość 20m (typ I) oraz na głębokość 100m (typ II). Wykazano, że największa wartość współczynnika COP występuje dla wymienników pionowych (typ I), nieco mniejsza dla wymienników poziomych i najmniejszą dla wymienników pionowych (typ II). Przeprowadzona analiza statystyczna wykazała, że rodzaj wymiennika wpływa istotnie na wartość COP; również średnie jego wartości są statystycznie istotne. Nie wykazano istotności wpływu temperatury wewnątrz obiektu na wartość współczynnika COP.

Key words: sprężarkowa pompa ciepła, pionowy, poziomy, wymiennik gruntowy.

# The analysis of oil balance in crank bearing

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 $c_{gr}$ D

S u m m a r y. The paper presents an analytical calculation of the balance of oil flowing through the dynamically loaded main and crank bearing. Theoretical considerations are based on solving the Reynolds equation (analytical distribution of oil pressure in the cross slide bearing) with boundary conditions that characterize the working conditions in the bearings used in motors s-4002/4003 (agricultural tractors). The quantitative and volumetric evaluations of lubricant fluid flowing through the bearing are presented adequately to the construction of a diagnostic signal, which allows for a dynamic comparative analysis carried out for the model bearings, the new ones as well as the ones with a particular classification of wear.

K e y w o r d s : hydrodynamic lubrication, cross slide bearing, Reynolds equation, diagnostic analysis, diagnostic signal parameters.

• Physical quantities

*h* - thickness of the wedge [*mm*],

- $\varepsilon$  relative bearing eccentricity [-],
- *c* bearing clearance [*mm*],
- $\eta$  coefficient of dynamic oil viscosity [Pa · s],

*V* - peripheral speed of crankshaft 
$$[m/s]$$
,

*e* - eccentricity [*mm*],

$$P(x,z)$$
 - oil pressure inside bearing [Pa],

$$\begin{array}{rcl} x,z & - \mbox{ coordinate variables}, x \in \langle 0, 2\pi R \rangle, z \in \left\langle -\frac{L}{2}, \frac{L}{2} \right\rangle \\ & [mm], \\ L & - \mbox{ the width of the pan } [mm], \\ p_w, p_0 & - \mbox{ supply pressure ambient pressure } [Pa], \\ p_z & - \mbox{ supply pressure } [Pa], \\ a & - \mbox{ cord diameter } [mm], \end{array}$$

Q - oil intensity passing through the crank bearing  $[dm^3/min]$ ,

$$Q_1, Q_2$$
, - partial intensity[ $dm^3/min$ ],

$$S_{0'}S_{gr}$$
 - values for  $Q_1$ ,  $Q_2$  from experiment  $[dm^3/min]$ ,  
 $h_0 = \min_{x \in \langle 0, 2\pi R \rangle} h(x)$  - minimum thickness of oil wedge

$$c_{dot} = c_0$$
 - clearance after getting proper association (at optimal operation after 100mth) [*mm*],

- critical value of clearance [mm],

- coefficent of dinamic passing [-],

- experimenthal value of  $D_p$  determined as a parametr of the diagnostic signal

• Mathematical solutions

$$\Delta [f]_{a}^{"} = f(a) - f(b) \quad \text{- differential operator}$$
$$f_{K} = \sum_{k=1}^{K} f_{k} \quad \text{- summing operator, } \mathbf{N},$$

[f] - total part of expression f,

 $C_P C_{IP} C_{IK}$  - Reynolds equation constants determined by boundary conditions

## INTRODUCTION

The parameters of diagnostic signals defining the course of change in the tightness of slide bearings are a very important factor in assessing the technical state of engines examined in this study on the example of farm tractors. It should be noted that in the lubrication subsystem the main slide bearings and the crank ones of the crankshaft determine the technical condition of the engine, and its ability to perform useful functions. Increased clearances in the bearings make the lubricant oil flow freely through the gaps between the pivots and the cups, which in turn is manifested by an increase in oil flow and pressure drop in the engine lubrication system.

In diagnostic considerations, the evaluation of work behavior of a dynamically loaded slide bearing is based on the simplified model of a standard cross slide bearing and is based mostly on the minimum thickness of oil gap and the value of the maximum pressure and maximum temperature of the oil film. However, as noted by several authors [1,2,4,7,17], in diagnostic tests, particularly in predicting the technical state of emergency crank system operation, application of a single-parameter diagnostic signal based solely on the measurement of relative drop in oil pressure at selected points of the bearing, is not sufficient to assess the degree of bearing wear. [18,17] presented a multivariate statistical analysis (curvilinear regression model for the associated random variables) of the diagnostic signal based on measurements of four parameters, where the measurement of the relative pressure drop and loss of lubricant in the bearings were considered as associated variables. The purpose of this study is to analyze the theoretical value of the diagnostic signal parameter described by an analytical balance of oil in the cross slide bearing.

In diagnostic studies of changes in oil flow through the crankshaft bearing and at the constant supply pressure in static conditions, the oil flow rate depends mainly on the size of oil gap. And according to the relation:

$$h = L_{\epsilon}(1 - \varepsilon \cos\theta),$$

the gap value depends on oil bearing clearance  $(L_i)$ and relative bearing eccentricity ( $\epsilon$ ), in further considerations we use a simplified designation:

 $L_t = c$ .

Determination of this value in the experimental way is based on measurements of diagnostic parameters, the commonest of which are oil pressure or relative drop of oil pressure in the lubrication subsystem (bearing seal). By way of contrast, the theoretical determination of the oil gap is based on the equations of hydrodynamics for a viscous substance.

## MATHEMATICAL MODEL OF BEARING AND ASSUMPTIONS

Assessment of work of dynamically loaded crank bearing is one of the most important tasks of the crank subsystem diagnostics in internal combustion engines. In this paper, theoretical considerations and the resulting mathematical calculations are shown on the basis of a cross slide bearing model, characterizing the operating parameters of crank bearing in S-4002/4003 type of internal combustion engines. In the process of exploitation, the growing bearing clearance values cause an increase in the impact of oil flowing from the bearing, causing a decrease in tightness of the bearings.

The balance of oil flowing through a dynamically loaded crank bearings can be determined analytically using a pressure distribution which is the solution of the Reynolds equation:

$$\frac{\partial}{\partial x} \left( \frac{h^3}{\eta} \frac{\partial P}{\partial x} \right) + \frac{\partial}{\partial z} \left( \frac{h^3}{\eta} \frac{\partial P}{\partial z} \right) = 6V \frac{\partial h}{\partial x}.$$
 (1)

After considering the constant coefficient of dynamic oil viscosity ( $\eta = const$ ) as well as the following simplified expressions for the functions describing the thickness of the wedge and the bearing wear [5,9,14,20]:

$$h = h(x) = c \left( 1 - \varepsilon \cos \frac{x}{R} \right), \tag{2}$$

$$\frac{3}{h(x)}\frac{\partial h(x)}{\partial x} = \frac{3e\sin \frac{x}{R}}{Rc\left(1 - \varepsilon \cos \frac{x}{R}\right)},\tag{3}$$

equation (1) can be written as:

$$P''_{xx}(x,z) + P''_{zz}(x,z) + \frac{3e\sin\frac{x}{R}}{Rc\left(1 - \varepsilon\cos\frac{x}{R}\right)}P'_{x}$$
$$(x,z) - \frac{6\eta e\sin\frac{x}{R}}{Rc^{3}\left(1 - \varepsilon\cos\frac{x}{R}\right)^{3}}V = 0, \qquad (4)$$

with the boundary conditions:

$$P = p_0 \text{ for } z = \pm \frac{L}{2}, \tag{5}$$

$$P = p_w(x) \text{ for } z = 0, \tag{6}$$

$$\left(\frac{\partial P(x,z)}{\partial z}\right)_{W} = -\frac{3\pi a^{4} \left(p_{z} - p_{w}\right)}{4c^{3}\eta L \left(1 - \varepsilon \cos \frac{x}{R}\right)^{3}} \text{ for } z = 0$$
(7)

where:

 $p_0$  - the ambient pressure [Pa],

- $p_z$  supply pressure [Pa],
- $p_w$  oil pressure at the inlet to the placenta [Pa],
- *a* cord diameter [mm],
- L width of the pan [mm].

According to [5,12,14], the analytical distribution in the bearing oil pressure as the solution of equation (4) can be written as follows:

$$P(x,z) = p_0 + C_1 \left( z - \frac{L}{2} \right) + \left[ \frac{1 - \varepsilon \cos \frac{x}{R}}{1 + \varepsilon} \right]^{-\frac{3e}{\varepsilon}} \cdot \frac{1 - \varepsilon \cos \frac{x}{R}}{1 + \varepsilon} \cdot \sum_{K=1}^{\infty} C_{1K} \left( e^{Kz} - e^{K(L-z)} \right) \left[ \Phi_{RK} \left( \frac{x}{R} \right) + \Psi_{RKV}^{-2} \left( \frac{x}{R} \right) \right], \qquad (8)$$

where:

$$\Phi_{RK}\left(\frac{x}{R}\right) = -\frac{\sin^2 \frac{x}{R}}{4} \left(\frac{1 - \cos \frac{x}{R}}{2}\right)^{-(R^2 K^2 + 1)}, \quad (9)$$

$$\Psi_{RKV}\left(\frac{x}{R}\right) = \left(\frac{2\pi RK}{nV}\right)^{2} \sum_{i=1}^{\left[R^{2}K^{2}\right]} \left[\left(\frac{R^{2}K^{2}V}{i}\right)\frac{1}{i}\left(\frac{1-\cos \frac{x}{R}}{2}\right) - \ln\left(\frac{1-\cos \frac{x}{R}}{1+\cos \frac{x}{R}}\right)^{i} - \left(\frac{1-\varepsilon\sqrt{V}\cos \frac{x}{R}}{\pi\left(1+e\sqrt{V}\right)}\right)^{\frac{3e}{\varepsilon}}\right],$$
(10)

$$C_{1} = \frac{\Delta_{L}}{1 + \frac{L}{2}\Delta_{L}} (p_{z} - p_{0}),$$
(11)

$$C_{11} = \frac{3\Delta_{L}\Gamma_{L}(p_{z} - p_{0})}{(1 + \varepsilon)^{\frac{3\varepsilon}{\varepsilon}} \left[1 + \frac{1 + \varepsilon}{1 - \varepsilon} \left(\Phi(0) + \Psi^{-2}(0)\right) - \left(\frac{1 + \varepsilon}{1 - \varepsilon}\right)^{\frac{3\varepsilon}{\varepsilon}} \left(\Phi\left(\frac{\pi}{2}\right) + \Psi^{-2}\left(\frac{\pi}{2}\right)\right)\right]}, (12)$$
$$\Delta_{L} = \frac{15\pi a^{4}}{2c^{3}\eta L}, (13)$$

$$\Gamma_{L} = \frac{1 - \varepsilon^{2}}{1 + 3\varepsilon} \Delta_{L} \left( e^{L} - 1 \right).$$
(14)

#### ANALYTICAL BALANCE OF OIL

Analytical determination of the amount of oil flowing through bearing is based on the solution of equation (4), i.e. function P (x, z) describing the distribution of pressure in the crank bearing [9,20]. The value of the intensity of Q passing through the crank bearing can be represented as two partial streams  $Q_1, Q_2$ , where  $Q_1$ is part of the stream flow caused by the rotation of the crankshaft, while  $Q_2$  is part of a stream of pressurized forced power  $Q_2$ . By virtue of the above considerations, the dependencies representing the partial streams of flowing oil can be written as follows:

$$Q_{1} = Q_{1,x=0} - Q_{1,x=R\pi} = \frac{1}{6\eta} \int_{-\frac{1}{2}}^{\frac{1}{2}} h^{3} \Delta \left[\frac{\partial P}{\partial x}\right]_{0}^{R\pi} dz =$$
$$= \frac{1}{6\eta} \int_{-\frac{1}{2}}^{\frac{1}{2}} h^{3} \left[\frac{\partial P}{\partial x}\right]_{x=0} dz - \frac{1}{6\eta} \int_{-\frac{1}{2}}^{\frac{1}{2}} h^{3} \left[\frac{\partial P}{\partial x}\right]_{x=R\pi} dz , \qquad (15)$$

$$Q_{2} = Q_{2,z=0} - Q_{2,z=\pm\frac{L}{2}} = \frac{1}{6\eta} \int_{0}^{2\pi} h^{3} \Delta \left[\frac{\partial P}{\partial z}\right]_{0}^{\pm\frac{\pi}{2}} dx =$$
$$= \frac{1}{6\eta} \int_{0}^{2\pi} h^{3} \left[\frac{\partial P}{\partial z}\right]_{z=0} dx - \frac{1}{6\eta} \int_{0}^{2\pi} h^{3} \left[\frac{\partial P}{\partial z}\right]_{z=\pm\frac{L}{2}} dx \quad , \tag{16}$$

where:

$$Q_{1,x=0} = \frac{c^3 C_{1K} \left(1 - \exp\left\{KL\right\}\right)}{6\eta RK}$$
$$\left(1 - \varepsilon\right)^3 \left(\frac{1 + \varepsilon}{1 - \varepsilon}\right)^{\frac{3\varepsilon}{\varepsilon}}, \qquad (17)$$

$$Q_{1,x=R\pi} = \frac{c^3 C_{1K} \left(1 - \exp\left\{KL\right\}\right)}{48\eta RK} \left(1 + \varepsilon\right)^3, \quad (18)$$

$$Q_{2,z=0} = \frac{c^3 K \pi \left(1 + \exp\left\{KL\right\}\right)}{6\eta} \left[2C_1 + \frac{C_{1K} \left(6e + \varepsilon\right)}{3e + 2\varepsilon} \left(1 - \varepsilon\right)^{\frac{3e}{\varepsilon}}\right], (19)$$

$$Q_{2,z=\pm\frac{L}{2}} = \frac{c^3 K \pi \exp\left\{KL\right\}}{3\eta} \left\{ 2C_1 + \frac{C_{1K} \left(6e + \varepsilon\right)}{3e + 2\varepsilon} \left(1 - \varepsilon\right)^{\frac{3e}{\varepsilon}} \right\}.$$
(20)

The relationships (17) - (20) omitted elements of the order  $o(\varepsilon^3)$  and used the following indications:

$$C_1 = -\frac{\Delta_L}{1 + \frac{L}{2}\Delta_L} (p_z - p_0), \qquad (21)$$

$$C_{1K} = \sum_{k=1}^{K} C_{1k} = \sum_{k=1}^{K} \left( p_0 - C_1 \frac{L}{2} + \left[ \frac{1-\varepsilon}{1+\varepsilon} \right]^{-\frac{3\varepsilon}{\varepsilon}} \frac{\Delta_L}{\pi C_1 \left( 1 - \frac{KL}{4} \right)} \right), (22)$$

where:

$$K = 1, 2, \dots, \left[ \left( \frac{R}{e} \right)^2 - 1 \right].$$
(23)

Due to (17) - (20), oil streams  $Q_1$ ,  $Q_2$  can be written as follows:

$$Q_{1} = \frac{c^{3}C_{1K}\left(1 - \exp\left\{KL\right\}\right)}{6\eta RK} \left[ (1 - \varepsilon)^{3} \left(\frac{1 + \varepsilon}{1 - \varepsilon}\right)^{\frac{3e}{\varepsilon}} - \left(\frac{1 + \varepsilon}{2}\right)^{3} \right], (24)$$
$$Q_{2} = \frac{K\pi\left(1 - \exp\left\{KL\right\}\right)}{6\eta} \left[ 2C_{1} + \frac{C_{1K}\left(6e + \varepsilon\right)}{3e + 2\varepsilon} \left(1 - \varepsilon\right)^{\frac{3e}{\varepsilon}} \right]. (25)$$

Finally, by equation (15), (16), the balance of oil flowing through the crank bearing can be written as the following relationship:

$$Q = Q_1 + Q_2 = \frac{c^3 \left(1 - \exp\{KL\}\right)}{6\eta} \left[ 2C_1 + C_{1K} \left(\frac{\Omega_1}{RK} + K\pi\Omega_2\right) \right], (26)$$

where:

$$\Omega_1 = (1 - \varepsilon)^3 \left(\frac{1 + \varepsilon}{1 - \varepsilon}\right)^{\frac{3\varepsilon}{\varepsilon}} - \left(\frac{1 + \varepsilon}{2}\right)^3, \tag{27}$$

$$\Omega_2 = \frac{6e + \varepsilon}{3e + 2\varepsilon} (1 - \varepsilon)^{\frac{3e}{\varepsilon}}.$$
(28)

# PERFORMANCE ANALYSIS OF DIAGNOSTIC SIGNAL

In the crank bearings of the engine type S-4002/4003 (agricultural tractors C-355, 360), the maximum value of bearing clearance is characterized by accelerated wear of crank mechanism (the boundary condition of the bearing crank is 0.2 mm), which can be derived from the average dependence given by [10,20,21]:

$$C_{gr} = \frac{C_{dot}^2}{4h_0},\tag{29}$$

using the classical formula Vogelpohl:

$$C_{dot} = 0.92 \cdot 10^{-3} \sqrt[4]{V}, \tag{30}$$

where:

 $C_{\rm dot}$  - clearance after getting proper association (at optimal operation after 100mth),

 $h_0$  - the minimum thickness of oil wedge,

V - the peripheral speed of crankshaft.

In the boundary conditions of dynamically loaded crank bearing's operation, the diagnostic signal parameters describing the relative decline in the oil pressure inside the bearing and its flow through the bearing score significantly higher values than when working under optimal conditions, which points to accelerated wear of the crank. Piekarski [17] applied the model to assess the value of diagnostic signal parameters based on measurements of the relative pressure drop and oil flow dynamics at the measurement narrowing. As an indicator of the dynamics, the following value describing oil flow through the bearing was accepted:

$$d_{p} = \frac{S_{gr} - S_{0}}{S_{0}},$$
(31)

Analytical interpretation of the above relation, using the average value of clearance limit (at the speed of the shaft 1200 min<sup>-1</sup>):

$$C_{gr} = 2,3 \cdot 10^{-3} \sqrt{V} = 1,42 \cdot C_0$$

can be obtained by equation (26) as follows:

$$D_{p} := \left(\frac{c_{gr}}{c_{0}}\right)^{3} \cdot \frac{2C_{1} + C_{1K}\left(\frac{\Omega_{1gr}}{RK} + K\pi\Omega_{2gr}\right)}{2C_{1} + C_{1K}\left(\frac{\Omega_{10}}{RK} + K\pi\Omega_{20}\right)} - 1 = 2,86 \cdot \frac{\Phi_{gr}}{\Phi_{0}} - 1,(32)$$

where:

 $\Omega_{_{i0}}$  - quantity calculated from solutions (27),(28) for  $c=c_{_0},\,i{=}1{;}2{,}$ 

 $\hat{\Omega}_{igr}$  - quantity calculated from solutions (27),(28) for  $c = c_{gr}$ , i=1;2,

$$\begin{split} \Phi_{0} &= 2C_{10} + C_{1K} \left( \frac{\Omega_{10}}{RK} + K \pi \Omega_{20} \right), \\ \Phi_{gr} &= 2C_{1gr} + C_{1K} \left( \frac{\Omega_{1gr}}{RK} + K \pi \Omega_{2gr} \right), \\ K &= \begin{cases} 1 & \text{for } c = c_{0} \\ 2 & \text{for } c \in (c_{0}, c_{gr}) \end{cases} \end{split}$$

 $\begin{bmatrix} 3 & for \ c = c_{gr} \end{bmatrix} .$ 

In diagnostic tests, the dynamic of determined signal changes should be as high as possible. It is assumed that the determined change induced by an increase in consumption occurring in the crank subsystem is the relative increase in oil pressure drop, which is treated as a diagnostic signal.

#### CONCLUSIONS

Knowledge of the dynamics of steam friction (pivot - cup) in a crank system, expressed by escalation of clearance between its elements, allows to determine the probability of reliable operation of the considered friction pair. A proper technical maintenance of the engine operation is necessary, provided the information is available on its properties.

This information can be known only by the changes of bearing clearance and course changes in the dynamics of the diagnostic signal.

Terms of co-operation of the functional subsystem crank pivot - cup decide on the reliable operation of the engine. The worsening conditions for cooperation of these subsystems as a result of processes of consumption leads to premature engine wear, and even more to significant increase in fuel and oil consumption and increased difficulty in starting.

Requirements for operational progress are becoming more frequently recognized and formulated. It was noted that the effectiveness of the management of technical objects in many cases reduces the high operating expenses, which may even get higher than expenses associated with designing and manufacturing. The high operating expenses can be reduced by improving the quality of technical objects, as well as conditions of their use and handling. For this purpose, the pursuit is necessary of rational, science-based exploitation of technical objects.

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#### ANALIZA BILANSU OLEJU W ŁOŻYSKU KORBOWYM

S tr e s z c z e n i e. Praca przedstawia analityczną kalkulację bilansu oleju przepływającego przez dynamicznie obciążone łożysko główne i korbowe. Teoretyczne rozważania bazują na rozwiązaniu równania Reynoldsa (analityczny rozkład ciśnienia oleju w łożysku poprzecznym ślizgowym) o warunkach brzegowych charakteryzujących warunki pracy w/w łożysk zastosowanych w silnikach S-4002/4003 (ciągniki rolnicze). Ilościowo-objętościową ocenę cieczy smarującej przepływającej przez łożysko przedstawiono adekwatnie do teoretycznej wartości sygnału diagnostycznego co pozwala na dynamiczną analizę porównawczą przeprowadzoną dla wzorcowych, nowych, jak również dla łożysk o ustalonej klasyfikacji stopnia zużycia.

Słowa kluczowe: smarowanie hydrodynamiczne, łożysko poprzeczne ślizgowe, równanie Reynoldsa, analiza diagnostyczna, parametry sygnału diagnostycznego.

# The physicochemical evaluation of oils used for frying chips in the aspect of biofuel production

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Summary. Plant oils used for frying food in industrial or household conditions undergo degradation resulting from multi directional physicochemical transformations. Post-frying fat may be utilized for production of FAME type biofuel. Goal of this paper were analysis of physicochemical changes taking place in sunflower and rapeseed oil during course of potato chips frying process, and answer to a question concerning effect of type of oil, number of frying cycles and addition of chips on above mentioned changes, when compared with fresh oil. This answer will provide information concerning suitability of investigated post frying oils for production of biofuels. With rapeseed and sunflower oils used for frying chips as examples, verification of hypothesis of lack of significance of intergroup factors effects: oil and additions of chips, was conducted. Significance of frying cycle and its interactions with intergroup factors was also verified. Influence of type of oil and chips addition on four chosen oil quality parameters: acid number, peroxide number, fatty acids oxidation products, photometric colour index, was compared. Moreover, interactions between investigated factors and frying cycle were analysed. In order to verify hypotheses of lack of significance of intergroup factors effects, univariation variance analysis was used, in spite of strong linear dependence between investigated parameters of oil: acid number (AN), peroxide number (PN), oxidation products (OP) and photometric colour index (PCI). Number of oil samples was too small when compared to number of dependent variables, what lead to necessity of using univariation test. It must be noted that dependence between these variables is not cause and effect one. Values of particular variables depended on cycle of heating, while they did not depend on other variable investigated in the research. Significance of factor of repeated measurements and its interactions with intergroup factors were verified by means of multivariation variance analysis and univariation tests F.

Key words: post-frying oils, biofuels, acid number, peroxide number, PCI, variance analysis.

#### INTRODUCTION

Plant oils used for frying food in industrial or home conditions are subject to degradation resulting from multi

directional physicochemical changes caused by high temperature, water and atmospheric oxygen. Reactions taking place in fat subjected to prolonged heating depend on conditions in which frying is conducted, initial quality of utilized oil, type of food and its surface, content of water and antioxidants as well as concentration of oxygen and type of fryer. High temperature of frying, number of cycles, content of free and unsaturated fatty acids, ions of heavy metals, food additives with remnants of agents for cleaning and washing equipment, lower oil's resistance to oxidation and are factors increasing pace of disadvantageous oil quality changes [1, 3]. Volatile and non-volatile substances are products of the reactions. Most of them evaporate with water vapour and remaining ones take part in reactions of oxidation and polymerization or are absorbed by food. Some, formed during frying, volatile compounds (1,4-dioxane, benzene, toluene) do not contribute to obtaining desirable taste and are toxic [14, 4]. High temperature and sunlight accelerate formation of free radicals and, as result of it, affect free-radical chain transformations. Water, weak nucleophile, attacks ester bounds of triglycerides and and this way di- and monoacylglycerides, glycerol and free fatty acids are formed. Thermal hydrolysis is observed mainly in oil phase. Products of hydrolysis reactions undergo secondary oxidation transformations [19]. Oxidation leads to formation of hydroperoxides and volatile, low particular weight, compounds such as aldehydes, ketones, carboxylic acids, alkanes and short chain alkenes, and high temperature favours processes of cyclization [4, 14].

In deeper layers of oil, where access of oxygen is limited, transformations leading to formation of free radicals, which are precursors of polymerization transformations of oil, prevail. Formation of polymers results in changes of density, viscosity and consistence of fat [22]. Polymers, formed in frying oil as a result of oxidation and thermal transformations, directly contribute to intensification of hydrolytic changes, for they cause detergency of oil, this way promoting accumulation of water vapour in frying oil. Detergency of frying oil favours also reactions of free fatty acids with, present in fried product, cations of sodium and potassium [4, 8]. As a result of fat degradation, surfactants, which increase time of contact of food and oil, are formed. Therefore quantity of fat absorbed by food increases, what causes decrease of heat transfer rate and decrease of heat transport factor [2].

In fats subjected to prolonged heating, changes of colour, intensifying with time that frying oil is used, occur. Main cause of colour changes are oxidation reactions, leading to accumulation of non-volatile compounds in fryer - mainly polymers. Maillard compounds, formed of remains of food present in frying oil, are also reason for frying oil darkening. Moreover, all fried products may affect colour of fat, by releasing into frying oil coloured substances and lipids [8, 7, 12]. Changes of colour can be used as indicator helping to control course of the process.

Increase of production of post-frying wastes from households and from industrial production becomes more and more significant problem both in Poland and the world. Unfortunately, this waste is often dumped into sewer system, what creates problem for waste water treatment plants and leads to loses of energy. Obtained, by means of properly organised and selective collection, post-frying oil can be utilized for production of FAME (Fatty Acid Methyl Esters) and can be used as biofuel. Elaboration of criteria enabling determination of: when oil is not suitable for use, and what its maximal save degree of "wear out" is, poses a great challenge for producers of fried food. Similar problem concerns used frying oils intended for transesterification reaction. Such oils shall characterize with specified values of acid and peroxide number and of free fatty acids [6].

Fuels for diesel engines, obtained from edible oils are changing electricity markets. To decrease production costs more and more often used vegetable and animal fats additives are used as raw materials. Quality requirements for these materials, pertaining to the content of free fatty acids, water, phosphatides and solid impurities depend on the kind of catalyst used. In FAME production these are alkaline catalysts, acidic catalysts or enzymes. With acidic catalysts usage even a 50 % or higher content of free fatty acids (FFA) in oils is accepted. With alkaline catalysts this should not exceed 0.5 - 1 % [9, 21]. High FFA content in fat causes significant loses in catalyst reaction, as in KOH due to potassium soaps formation. Post-frying oils quality parameters such as unsaturated fatty acids products colour and quantity are degradation degree indicators. Esters obtained from strongly degraded fats can be used as an additive to fuel oil.

Aim of this paper were analysis of physicochemical changes taking place in sunflower and rapeseed oil during course of chips frying process, and answer to question concerning effect of type of oil, number of frying cycles and addition of chips on above mentioned changes, when compared with fresh oil. This answer will provide information on suitability of investigated post-frying oils for production of biofuels. With rapeseed and sunflower oils used for frying chips as examples, verification of hypothesis of lack of significance of intergroup factors effects: oil and additions of chips, was conducted. Significance of frying cycle and its interactions with intergroup factors was also verified.

Characteristics of post-frying oils properties can be a basis for elaboration of model of these changes. Above mentioned research will enable elaboration and suggesting easy to conduct and cheap method of determination of quality of oil used for gastronomical purposes with regard to feasibility of its utilization for FAME production.

## MATERIALS AND METHODS

Sunflower and rapeseed oils were objects of this investigation. For the purpose of which 5 litres of each, obtained from batch in trade, were used. Content of individual containers was poured into a single container and mixed. Obtained mixture was called raw sunflower oil or raw rapeseed oil. Next, oil was heated in the container to temperature enabling proper frying of chips, which were made of raw potatoes. After frying and separation of potato chips, oil had been left in the container in room temperature for 24 hours. Collected sample was marked as frying I. After 24 hours remaining oil was heated again and all described above actions were repeated - yielding another sample marked as frying II. Whole process of heating, cooling and sampling was repeated until it yielded samples marked with numbers III, IV, V, VI and VII. In order to investigate effect of frying on properties of sunflower or rapeseed oil, similar cycles of heating and cooling, but without frying chips, were conducted yielding samples marked as heating I - VII.

Each of collected samples was subject to a laboratory testing and following properties were determined: peroxide number (PN) [15], acid number (AN) [16], photometric colour index (PCI) [14] and composition of higher fatty acids [18].

Photometric colour index (PCI) was determined by means of spectrophotometric method measuring absorbency for four lengths of light waves: 460 nm, 550 nm, 620 nm and 670 nm. Photometric colour index (PCI) was calculated as follows:

$$PCI = 1,29 \cdot (Ab_{460}) + 69,7 \cdot (Ab_{550}) + 41,2 \cdot (Ab_{670}) - 56,4 \cdot (Ab_{670}),$$

where:  $Ab(_{460})$ ,  $Ab(_{550})$ ,  $Ab(_{620})$ ,  $Ab(_{670})$  are values of absorbency measured for four lengths of light waves: 460 nm, 550 nm, 620 nm and 670 nm respectively [14]. After each heating, each oil sample (with and without chips) was analysed in six repetitions.

Determination of fatty acids composition was conducted by means of gas chromatography. Extracted fat was subjected to alkaline hydrolysis with sodium hydroxide solution in anhydrous methanol, and than released fatty acids were transformed into methyl esters with hydrogen chloride in methanol. Obtained esters were separated in a chromatographic column and than their participation in a sum of fatty acids was determined [18]. Relying on obtained chromatograms amount of oxidation products (OP) after each of seven frying cycles was calculated.

Investigation was conducted in randomised, complete design, according to two-factor, crossed classification scheme with repeated measurements. Crossed classification was used for two intergroup factors: oil and additives. Cycles of frying in temperature enabling preparation of potato chips were factor of repeated measurements. Statistical calculations were conducted by means of Statistica 6.0 program.

#### **RESULTS AND DISCUSSION**

In this paper, characteristics of chosen physicochemical changes of sunflower and rapeseed oil after each of the seven heating cycles, were evaluated. Analysed changes of acid number (AN), peroxide number (PN), photometric colour index (PCI) and oxidation products (OP) were presented in a graphic and tabular form in figures 1-4 and tables 1-3.

Raw sunflower and rapeseed oil characterized with typical properties meeting quality standards [17] of product being a subject to business trade; (rapeseed oil AN=0,192 mgKOH·g<sup>-1</sup>t of fat, PN=33 meq·kg<sup>-1</sup>, sunflower oil AN=0,111 mgKOH·g<sup>-</sup> of fat, PN=33,3 meq·kg<sup>-1</sup>). Oils were lucid, clear – no residuum was noted.

Influence of type of oil and addition of chips, on chosen oil quality parameters: AN, PN, OP and PCI, were compared. Moreover, interactions between investigated factors and frying cycle were analysed.

In order to verify hypothesis of insignificance of effects of intergroup factors univariation variance analysis was used, even though strong linear dependence between investigated parameters of oil: acid number (AN), peroxide number (PN), oxidation products (OP) and photometric colour index (PCI) was noted. Number of oil samples was too small when compared to number of dependent variables, what lead to necessity of using univariation test. It must be noted that dependence between these variables is not cause and effect one. Values of particular variables depended on cycle of heating, while they did not depend on other variable investigated in the research. Significance of factor of repeated measurements and its interactions with intergroup factors was verified by means of a few methods: multivariate variance analysis and univariate tests F.

#### ANALYSIS OF VARIABLE AN - ACID NUMBER

Results of multivariate Roy's test for repeated measurements factor - cycle of heating and its interactions with intergroup factors: type of oil and additives, leads to rejection of null hypotheses assuming insignificance of heating cycle influence and insignificance of interaction of heating cycle and intergroup factors on diversification of acid number of investigated oils (tab. 2).

Mauchley's test for sphericity does not reject null hypothesis assuming fulfilment of sphericity condition for acid number AN (tab. 3), what enables utilization of univariation tests for repeated measurements factor. At significance level of 0,01, significant diversification of acid number value, depended on type of oil, additives and heating cycle, was noted. Acid number of investigated oils was not changing identically with a change of additive and change of heating cycle (tab. 1).

Rapeseed oil with addition of chips maintained higher value of acid number AN throughout all heating cycles, while in pure rapeseed oil acid number levelled with AN of sunflower oil in the sixth heating cycle (fig. 1).

In sunflower oil heated without chips, acid number (AN) was growing systematically while oil was being heated, reaching finally level almost five times higher than in raw oil. In analogous sample of oil heated with potato chips, two-time increase was noted (fig. 1). In rapeseed oil, increase of acid number was 2.96 and 1.92 respectively.

Similar tendency of changes of investigated oils properties was observed in earlier research by Szmigielski et

Variable	Sources of variation	SS	Degrees of freedom	MS	F	р
	Absolute term	9.6587	1	9.6587	96093.82	0.000000
	Oil	0.2361	1	0.2361	2348.70	0.000000
	Additives	0.6424	1	0.6424	6390.76	0.000000
	Oil*additives	0.0171	1	0.0171	170.43	0.000001
AN	Error	0.0008	8	0.0001		
AN	Cycle	0.7197	7	0.1028	2465.72	0.000000
	Cycle*oil	0.0122	7	0.0018	41.91	0.000000
	Cycle*additives	0.1526	7	0.0218	522.88	0.000000
	Cycle*oil*additives	0.0359	7	0.0051	122.86	0.000000
	Error	0.0023	56	0.00004		

Table 1. Univariate analysis of variance analysis for investigated variables and factor of repeated measurements

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	Absolute term	50679.17	1	50679.17	298288.3	0.000000
	Oil	5541.31	1	5541.31	32615.1	0.000000
	Additives	252.33	1	252.33	1485.2	0.000000
	Oil*additives	573.89	1	573.89	3377.8	0.000000
DN	Error	1.36	8	0.17		
PN	Cycle	8031.86	7	1147.41	4830.9	0.000000
	Cycle*oil	826.15	7	118.02	496.9	0.000000
	Cycle*additives	557.89	7	79.70	335.6	0.000000
	Cycle*oil*additives	142.49	7	20.36	85.7	0.000000
	Error	13.30	56	0.24		
	Absolute term	91854.57	1	91854.57	169250.3	0.000000
	Oil	257.99	1	257.99	475.4	0.000000
	Additives	9612.67	1	9612.67	17712.2	0.000000
	Oil*additives	547.28	1	547.28	1008.4	0.000000
0.5	Error	4.34	8	0.54		
OP	Cycle	9293.11	6	1548.85	3797.4	0.000000
	Cycle*oil	3410.56	6	568.43	1393.6	0.000000
	Cycle*additives	1117.02	6	186.17	456.4	0.000000
	Cycle*oil*additives	246.20	6	41.03	100.6	0.000000
	Error	19.58	48	0.41		
	Absolute term	850492014	1	850492014	5254948	0.000000
	Oil	1106306	1	1106306	6836	0.000000
	Additives	23378872	1	23378872	144451	0.000000
	Oil*additives	844088	1	844088	5215	0.000000
DCI	Error	1295	8	162		
PCI	Cycle	128146166	7	18306595	196264	0.000000
	Cycle*oil	8358142	7	1194020	12801	0.000000
	Cycle*additives	22759271	7	3251324	34857	0.000000
	Cycle*oil*additives	4237936	7	605419	6491	0.000000
	Error	5223	56	93		



Fig. 1. Changes of acid number AN in subsequent heating cycles.F(7, 56)=122.86, p=0.0000. Vertical bars represent 0.95 confidence interval

	Sources of variation	Value	F	Effect df	Error df	p
	Cycle	62936.27	17981.79	7	2	0.000056
Variable AN	Cycle*oil	729.35	208.39	7	2	0.004784
	Cycle*additives	16450.86	4700.25	7	2	0.000213
	Cycle*oil*additives	3421.34	977.53	7	2	0.001022
	Cycle	73906.36	21116.10	7	2	0.000047
DN	Cycle*oil	38132.80	10895.08	7	2	0.000092
PN	Cycle*additives	7240.41	2068.69	7	2	0.000483
	Cycle*oil*additives	1554.84	444.24	7	2	0.002248
	Cycle	23783.68	11891.84	6	3	0.000001
OD	Cycle*oil	9055.49	4527.75	6	3	0.000005
OP	Cycle*additives	2997.96	1498.98	6	3	0.000027
	Cycle*oil*additives	1053.61	526.81	6	3	0.000128
	Cycle	6681140	1908897	7	2	0.000001
DCI	Cycle*oil	505382	144395	7	2	0.000007
PU	Cycle*additives	1203929	343980	7	2	0.000003
	Cycle*oil*additives	173356	49530	7	2	0.000020

Table 2. Multivariate Roy's test for factor of repeated measurements and for investigated variables

al. [20] and Maniak et al. [10]. This data suggests similar character of oil properties changes, of both rapeseed and sunflower oil, taking place during frying chips. In research of Chung [5] and Naz [13] it was showed that acid number and content of free fatty acids in oil sampled from frying pan was increasing with each frying cycle, while time of frying did not influence oil hydrolysis. Oxidation transformations seem to be a major profile of investigated oils changes. Samples in which chips were fried characterised with lower values of AN, when same number of frying cycle is taken into consideration, than samples heated without chips. It may result from minor influence of hydrolytic transformations of oil, taking place in presence of water from chips, as well as absorption of hydrolysis products on porous surface of potatoes.

#### ANALYSIS OF VARIABLE PN - PEROXIDE NUMBER

Peroxide number in sunflower oil was higher than in rapeseed oil regardless if chips were added or no addition of chips to heated oil was done. Addition of chips caused significantly slower increase of PN in rapeseed oil, while it only slightly slowed increase of this parameter in sunflower oil, hence, greater span between PN values in investigated oils (fig. 2). Similar trend was observed in case of properties of post-frying rapeseed and sunflower oils by Szmigielski [20] and Maniak [10].

It is characteristic in case of oxidation changes that initial high decrease of unsaturated fatty acids content is accompanied by simultaneous increase of products



**Fig. 2.** Changes of peroxide number PN in subsequent heating cycles. F(7, 56)=85.701, p=0.0000. Vertical bars represent 0.95 confidence interval

of partial fat oxidation content and increase of peroxide number. Above mentioned transformations are also probably affected by sorption of oxidation products by chips, what is suggested by lower peroxide number of samples heated with the product [4, 14, 19].

At significance level of 0.05 Mauchley's test for sphericity does not reject null hypothesis assuming fulfilment of sphericity condition for peroxide number - PN, while it rejects this hypothesis at significance level of 0,01 (tab. 3), therefore univariate test for repeated measurements factor shall be used with caution.

Results of multivariate Roy's test for repeated measurements factor - heating cycle and its interactions with intergroup factors, type of oil and additives, lead to rejection of null hypotheses assuming lack of significance of heating cycle influence and lack of significance of interactions of heating cycle with intergroup factors on diversification of peroxide number value PN in investigated oils (tab. 2). Univariate tests also reject null hypotheses for factor of repeated measurements and interactions of this factor with type of oil and additive (tab. 1). Therefore, at significance level of 0.01 significant diversification of PN level, with regard to type of oil, additives, heating cycle and interaction between these factors, was noted.

## ANALYSIS OF VARIABLE OP - OXIDATION PRODUCTS

Heating sunflower and rapeseed oil in laboratory conditions (small size of container used for the experi-

ment, and easy access of air), caused increase of content of partial fat oxidation products (OP), as a result of, characteristic mainly for oxidation processes, changes of composition of higher fatty acids (fig. 3). In investigated oils, amount of products of fatty acids oxidation (OP) was from 6.88% to 65.2% for sunflower oil heated without chips and from 4.8% to 62.2% for sunflower oil heated with chips, while respective values for rapeseed oil were from 27.24% to 49.48% and from 14.8% to 22.97%. Catalytic effect of present in heated oil potato chips (fig. 3), as well as sorption of oxidation products on surface of fried chips, are possible.

Autoxidation is radical chain reaction. It is greatly affected by food compounds like, for example: proteins, saccharides, food dyes and water as well as catalysts, which influence course and kinetics of autoxidation. Formed during oxidation of lipids hydroperoxides are very unstable, and hydrocarbons, aldehydes, ketones, alcohols and ethers are secondary products of their degradation [19].

At significance level of 0.05 Mauchley's test for sphericity does not reject null hypothesis assuming fulfilment of sphericity condition for oxidation products -OP, while it rejects this hypothesis at significance level of 0,01 (tab. 3), therefore univariate test for repeated measurements factor shall be used with caution. While at significance level of 0,01, significant diversification of oxidation products, with regard to type of oil, additives and heating cycle, was observed. It should be noted that content of oxidation products in investigated oils was not

Variable	Effect	W	Chi-kw.	df	р
AN	Cycle	0,001225	36,55609	27	0,103656
PN	Cycle		44.82426	27	0.016968
OP Cycle		0,001766	36,62489	20	0,012974
PCI	Cycle	0,001788	34,49470	27	0,152153

Table 3. Mauchley's sphericity test for investigated variables



Fig. 3. Changes of oxidation products OP in subsequent heating cycles. F(6, 48)=100.60, p=0.0000. Vertical bars represent 0.95 confidence interval



Fig. 4. Changes of photometric colour index PCI in subsequent heating cycles. F(7, 56)=6490.7, p=0.0000. Vertical bars represent 0.95 confidence interval

changing in the same manner in samples with and without addition of chips, and with each consecutive heating cycle.

In sunflower oil with addition of chips, content of oxidation products was increasing fast, while, in case of rapeseed oil with chips addition, slower increase was observed. Heating investigated oils without chips addition caused similar changes of content of oxidation products in cycles III-VI, while in second and seventh cycle of heating much greater increase of OP in rapeseed oil than in sunflower oil was observed (fig. 3).

Results of multivariate Roy's test for repeated measurements factor - heating cycle and its interactions with intergroup factors: type of oil and additives, lead to rejection of null hypotheses assuming lack of significance of heating cycle influence and lack of significance of interactions of heating cycle with intergroup factors on diversification of oxidation products of investigated oils (tab. 2). Univariate tests also reject null hypotheses for factor of repeated measurements and interactions of this factor with type of oil and additive (tab. 1). Therefore, at significance level of 0.01 significant diversification of OP level, with regard to type of oil, additives, heating cycle and interaction between these factors, was noted.

## ANALYSIS OF PCI - PHOTOMETRIC COLOUR INDEX

Visual and instrumental effect of changes taking place in subjected to heating seven times oils was their darkening progressing with time of their utilization. Main reasons for colour changes were oxidation reactions leading to accumulation of polymers in the fryer, as well as Maillard reactions in which simple and complex carbohydrates, proteins and amino acids, products of peroxides degradation were substrates [19, 11, 8].

Value of PCI for sunflower oil ranged from 1588 to 4730 for oil in which chips were fried, while for oil with no chips addition they were from 1588 to 4479. In case of rapeseed oil values were 842 - 5658 and 842 - 2543

respectively (fig. 4). Photometric colour index of oil was increasing faster in oil with chips addition than in pure oil. It must also be noted that the increase was faster in rapeseed oil than in sunflower oil. Course of changes of the index in oil without chips addition was similar. After seventh heating cycle value of PCI in rapeseed oil with chip addition was significantly higher than in same oil but without chips, while in case of sunflower oil, differences between PCI value of oil with and without chips were much smaller (fig. 4).

At significance level of 0,01, significant diversification of photometric colour index, with regard to type of oil, additives and heating cycle, was observed. Photometric colour index of investigated oils was not equally affected by addition of chips and by consecutive heating cycles (tab. 1). Relying on results of Mauchley's test, it was stated that sphericity condition for photometric colour index is fulfilled, therefore, univariate tests can by used for analysis of heating cycle effect (tab. 3).

Results of multivariate Roy's test for repeated measurements factor - heating cycle and its interactions with intergroup factors, type of oil and additives, lead to rejection of null hypotheses assuming lack of significance of heating cycle influence on diversification of photometric colour index of investigated oils, and lack of significance of interactions of heating cycle with intergroup factors (tab. 2). Univariate tests also reject null hypotheses for factor of repeated measurements and interactions of this factor with type of oil and additive (tab. 1). Therefore, at significance level of 0.01, significant diversification of PCI level, with regard to type of oil, additives, heating cycle and interaction between these factors, was noted.

#### CONCLUSIONS

1. Type of oil, additives (oil with or without chips) and frying cycles significantly diversify physicochemical properties of post-frying oils.

- 2. Changes of value of investigated parameters (AN, PN, OP, PCI) in investigated oils do not have same course, when changes of addition or heating cycle are taken into consideration.
- 3. Values of investigated parameters AN, PN, and OP in case of rapeseed oil with chips addition were at higher level than in sunflower oil.
- 4. Photometric colour index (PCI) of rapeseed oil with addition of chips increased significantly after third frying cycle, exceeding value of PCI recorded for sunflower oil with chips addition.
- 5. Course of changes of physicochemical properties of pure oils was similar for both investigated oils. Only in case of sunflower oil peroxide number PN increased significantly after first heating cycle and remained higher than in rapeseed oil throughout all subsequent heating cycles.
- 6. Results of conducted research may be a basis for elaboration of cheap and simple system of post-frying oils evaluation, when aspect of their use for biofuel production is considered.

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#### FIZYKOCHEMICZNA OCENA OLEJÓW UŻYWANYCH DO SMAŻENIA FRYTEK W ASPEKCIE PRODUKCJI BIOPALIW

Streszczenie. Oleje roślinne stosowane do smażenia w przemysłowych lub domowych warunkach ulegają degradacji wynikającej z wielostronnych fizykochemicznych transformacji. Tłuszcz pozostały po smażeniu może być wykorzystany do produkcji biopaliwa typu FAME.

Celem pracy była analiza fizykochemiczna zmian zachodzących w oleju słonecznikowym i rzepakowym podczas przebiegu procesu smażenia frytek ziemniaczanych, oraz ustalenie wpływu rodzaju oleju, liczby cyklów smażenia i dodatków do frytek na wyżej wymienione zmiany, w porównaniu ze świeżymi olejami. Wyniki badań pozwolą na wnioski dotyczące przydatności badanych olejów po smażeniu do produkcji biopaliw. Użyto olejów z rzepaku i słonecznika do smażenia frytek jako przykładów do weryfikacji założeń badawczych.

Słowa kluczowe: oleje po smażeniu, biopaliwa, liczba kwasowa, liczba nadtlenkowa, PCI, analiza warianeji.

# Biodegradation of TPS mouldings enriched with natural fillers

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Summary. The aim of the present study was to investigate the biodegradation of thermoplastic starch (TPS) mouldings in the soil. Samples, produced from mixtures of potato starch, glycerin and added fillers (natural fibers) were obtained in two steps: TPS granules by extrusion-cooking, than the extrudates were processed by injecting moulding technique to get mouldings. The varied weight loss of mouldings was observed during storage, depending the time of storage and raw materials composition. Those collected after 12 weeks of storage in the soil had the highest weight loss. It was noticed that the increased addition of glycerol in the mouldings had an effect on the higher degradation rate. To the contrary, the addition of fillers to the mouldings' composition, especially flax fibers, slowed down the process.

Key words: thermoplastic starch, extrusion-cooking, biodegradation, natural fibers

#### **INTRODUCTION**

Extrusion-cooking, popular in food processing, causes the destruction of starch and leads to its thermoplastic nature. Mixing and processing of starch with other components allows to form new materials – thermoplastic starch (TPS) used in packaging sector [6, 8, 17, 19, 20, 21].

TPS can be used as stand-alone packaging material or as an additive that improves the degradation of plastics. Its application is possible due to the relatively short time of degradation to  $CO_2$  and water. Biocomposites that are enriched with starch are mainly used in making films, containers, and in the production of foams used for filling of empty space contained in the packs [10, 14].

Packaging materials made from thermoplastic starch can be produced by two methods: single- and two-stage. A single-stage method involves prior formation of the components mixture and its application to the devices producing the packaging material. An example of such a device is an extruder, the universal machine widely used in plastic film production. A single-stage method is also used in the production of the mentioned before foams and fillers [5, 12, 13, 15]. In the case of two-stage method of production, the first step consists the production of TPS pellets – half-products processed by extrusion-cooking [11, 16]. The second stage is the production of packaging material, which can be performed with conventional equipment used in plastic processing, including film-blowing extruders and injection moulding machines.

#### MATERIALS AND METHODS

#### MATERIALS

The basic raw material was potato starch type Superior produced by AVEBE b.v. (NL), mixed with a technical glycerol of 99% purity produced by Odczynniki Chemiczne-Lublin (PL) – the plasticizer, and cellulose fibers vivapur type 102 (JRS GmbH, D) and flax fibers (Polish rural producers) – as the fillers.

#### PREPARATION OF MIXTURES

All ingredients were mixed using a laboratory ribbon mixer. The effective mixing time of 20 minutes was set after repeated attempts. The share of glycerol was 20%, 22% and 25% by the weight in the mixture, whereas the contribution of fibers in the prepared mixtures was 5% and 10%. After mixing, samples were left in sealed plastic bags for 24 hours in order to maintain the homogenous mixture. Immediately before the extrusion the blends were mixed once again for 10 minutes, which guaranteed getting looser structure of the mixture.

#### EXTRUSION-COOKING

TPS granules enriched with natural fibers were produced using a modified single screw extrusion-cooker type TS-45 (ZMCh Metalchem, PL) with L/D = 18/1, equipped with an additional cooling section of the barrel and a forming die with a hole diameter of 3 mm. Extrusion-cooking process temperature was set at the range from 60°C to 110°C and maintained appropriately adjusting the intensity of the flow of cooling liquid [1, 2, 3, 4].

# HIGH-PRESSURE INJECTION MOULDING

The high-pressure injection moulding machine AR-BURG 220H90-350 type, L/D=20.5 was used. The injection speed was maintained at (70-90) mm/s, the injection time: 5 sec., the process temperature ranged from 100° C to 180°C. Since the injection-moulded samples were used in the production, it gave the basic matrix in the form of 'shoulders', useful in the subsequent run-time tests of mechanical properties of moulded samples and their biodegradability. For biodegradability tests mouldings processed at 160°C were selected.

#### ASSESSMENT OF BIODEGRADABILITY TEST

The mouldings prepared with a moisture content of about 4% were placed in special baskets and stored in plastic boxes covered with 15 cm layer of garden soil with a moisture content of 70% and pH 6.5 for 2, 4, 8 and 12 weeks [18]. In order to ensure constant initial soil moisture, the content of soil and the process of water loss were determined twice a week (Fig. 1, 2).

The boxes with samples were kept in autumn in an unheated room at constant humidity at 15°C. Afterwards, mouldings were cleaned, weighed and dried to a moisture content of 4%. The determination of mass loss was carried out in the final stage of storage intervals [7, 9].



Fig. 1. The mouldings placed in the boxes with soil



Fig. 2. The distribution of samples in the boxes to the ground



Fig. 3. The influence of storage time and the amount of flax fibers on the weight loss of the mouldings containing 20% of glycerol

# RESULTS

The highest weight loss was observed after 12 weeks storage period for the whole range of the investigated samples. The results of the weight loss in mouldings containing 20% of glycerol and the addition of flax fibers are shown in Figure 3.

For all the samples after the first two weeks of storage, the recorded weight loss ranged from about 13% (for the samples containing 20% of glycerol) to approximately 23% (for the samples containing 25% of glycerol).

In the case of starchy samples without natural fibers, stored for 12 weeks, a greater weight loss at a higher content of glycerol in the formulation of granulates was observed. Moreover, the moulding's surface underwent decomposition faster in contact with moist soil than in its inner layer (the moulding's core).





Fig. 4. Samples with flax fibers after 12 weeks of storage

The addition of flax fibers influenced the degree of biodegradation. It was observed with the increase of the flax fibers content in the blend an increase in the weight loss of tested mouldings.

The highest weight loss, which reached about 56%, was observed in samples containing 10% of flax fibers after 12 weeks of storage. The samples processed without the addition of flax fibers characterized smaller weight loss, which was about 40% after 12 weeks (Fig. 4). The increase in the amount of plasticizer in the samples (22% and 25% of glycerol) increased the rate of biodegradation during the first 8 weeks of the experiment (Fig. 5, 6).

Weight losses of samples were greater than in the mouldings made from granulates containing 20% of glycerol. Mouldings with 22% of glycerol and 5% of flax fibers indicated the smallest weight losses during



Fig. 5. The influence of storage time and the amount of flax fibers on the weight loss of the mouldings containing 22% of glycerol



Fig. 6. The influence of storage time and the amount of flax fibers on the weight loss of the moulding 25% of glycerol

storage, reaching about 32% after 12 weeks (Fig. 5). The increase in the content of fibers from 5% to 10% in samples caused the increase in the weight loss by approximately 16%.

Samples made of granulate containing cellulose fibers of 5% and 10%, as well as those with the addition

of 20% of glycerol, indicated similar properties to the samples containing flax fibers (Fig. 7).

The addition of cellulose fibers influenced their biodegradation process. As it was observed, the increase of cellulose fibers in the blend resulted in the increase in the weight loss. The highest weight loss, which ranged from about 51%



Fig. 7. The influence of storage time and the amount of cellulose fibers on the weight loss of the mouldings containing 20% of glycerol

- 53%, was observed for the mouldings containing 5% and Fig



10% of cellulose fibers after 12 weeks of storage (Fig. 8).

Figure 9 presents a similar tendency, where the weight loss for tested samples produced from granulates containing cellulose fibers is similar to the weight loss for those containing flax fibers.

Within the course of the experiment it was proved that the mouldings containing cellulose fibers displayed the same quality as those with flax fibers. Numerous cracks and groves which occurred on the surface of compacts as the result of consecutive biodegradation were observed (Fig. 10).

Figure 11 presents the influence of storage time and amount of cellulose fibers on the weight loss of the mouldings.

The highest weight loss was observed for the samples made of granulate containing 25% of plasticizer without the addition of fibers. After 12 weeks the weight loss was about 57%. The addition of cellulose fibers resulted in the decrease of weight loss in comparison to the samples produced without fibers.

Samples prepared without the addition of fibers and those containing cellulose were fragile and prone to cracking during storage according to the weight loss. Samples containing flax fibers displayed good resistance to the damage.

#### CONCLUSIONS

It was indicated that the weight losses were higher with the increase of glycerol content in the mouldings.



Fig. 9. The influence of storage time and the amount of cellulose fibers on the weight loss of the mouldings containing 22% of glycerol





Fig. 10. The mouldings containing flax (a) and cellulose (b) fibers after 2 weeks storage time

The highest weight loss (ca. 57%) was observed in the samples with 25% of glycerol.

The increase in the content of flax fibers slowed down the process of decomposition in the first two weeks of storage. Numerous changes visible on the surface of mouldings in the early stage of storage (cracks, grooves, etc.) are considered to be the result of the consecutive biodegradation process.



Fig. 11. The influence of storage time and the amount of cellulose fibers on the weight loss of mouldings containing 25% of glycerol

The addition of flax and cellulose fibers resulted in quicker biodegradation process in soil, which was observed in the final stage of storing (after 12 weeks).

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#### BIODEGRADACJA WYPRASEK SKROBI TERMOPLASTYCZ-NEJ WZBOGACONYCH NATURALNYMI WYPEŁNIACZAMI

Streszczenie. Badaniom poddano formy sztywne w postaci wyprasek wytworzonych ze skrobi termoplastycznej (TPS). Granulaty zostały wyprodukowane z mieszanek skrobi ziemniaczanej, gliceryny oraz dodatku wypełniaczy w postaci włókien naturalnych. Następnie formy sztywne w postaci wyprasek wytworzono metodą wtrysku wysokociśnieniowego z granulatów TPS charakteryzujących się zróżnicowaną zawartością gliceryny (plastyfikatora) i włókien (substancje wzmacniające). Podczas pomiarów zaobserwowano zróżnicowany ubytek masy wyprasek zależny od czasu ich przechowywania w glebie. Po 12 tygodniach przechowywania w glebie stwierdzono najwyższy ubytek masy próbek. Zwiększenie dodatku gliceryny w wyprasec wpływało na większe tępo biodegradacji natomiast dodatek wypełniaczy szczególnie włókien lnianych proces ten spowalniał.

Słowa kluczowe: skrobia termoplastyczna, ekstruzja, biodegradacja, włókna naturalne

# Cast agricultural tools for operation in soil

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Summary. This paper describes new cast designs of agricultural tools operating in soil. Using previous experience with the implementation of new ADI cast shares for reversible ploughs and single-sided ploughs, the design and appropriate technology were developed to cast subsoiler coulters and cultivator duckfoot. These castings were heat treated (austempered) and used in performance tests. The development of these tools, innovative in terms of their shape geometry and selection of suitable cast material resistant to extra heavy operating conditions, improved the functionality and prolonged service life of the agricultural machinery.

Key words: iron alloys, ductile iron, ADI, computer simulation, agricultural tools.

## INTRODUCTION

For many years the Foundry Research Institute in Cracow has been cooperating with the Industrial Institute of Agricultural Engineering in Poznan in the development of new designs and selection of materials for cast agricultural tools operating in soil to replace the components forged and welded [9, 10, 15-17]. As a result of this cooperation, a share was designed and cast to operate in the home-made reversible and single-sided ploughs. It won numerous medals and awards at home and abroad.

Currently, work is underway on new solutions. Among other things, castings of subsoiler coulter and cultivator duckfoot were designed, manufactured and submitted in a patent office.

## CASTING OF CULTIVATOR DUCKFOOT

Cultivator duckfoot operates during field work in soil under the conditions of tribological wear. The technology applied so far to make this tool has been punching and forging of steel components, followed by drilling, welding, grinding, and applying a corrosion-resistant coating. A photograph of this tool working directly in the soil during pre-sowing land cultivation is shown in Figure 1.



Fig. 1. A photograph of forged duckfoot for the cultivator spring teeth

As a part of the ongoing work, a new innovative design of the cast duckfoot was developed. Documentation was elaborated, adapting the design of the tool to the operating conditions and casting manufacturing technology. Illustrative models were prepared next, using the design method based on CAD and Solid Works giving the possibility of any arbitrary shaping and modelling of elements, allowing for the type and intensity of loading applied to them. Figure 2 shows the developed models of a duckfoot for the cultivator spring teeth. A virtual model and a real model in the version selected for tests are shown in respective drawings.



**Fig. 2.** Duckfoot for the cultivator spring tooth: virtual 3D model made in Solid Works (left) and pattern made by RP on a 3D DIMENSION 1200es printer (right)

The casting technology was developed by computer simulation. The simulation has shown that:

- reduced temperature of pouring and lower initial mould temperature reduce the casting porosity,
- the porosity is also reduced by proper treatment of liquid metal with a good degree of graphitisation,
- technology no. 2 where the technological mould component is shifted to the lower part of casting (Figure 3) reduces porosity in places of the hot spots during casting solidification.





Fig. 3. Drawings of the two examined technologies

The cast iron of composition given in Table 1 was used for a pilot batch of duckfoot castings made according to technology no. 2. A photograph of these castings is shown in Figure 4.

Table 1. The results of chemical analysis of the melt

Ductile	Chemical composition; wt.%								
iron	С	Si	Mn	Р	S	Mg	Ni	Mo	Cu
nickel- copper	3,60	2,45	0,32	0,035	0,020	0,065	1,90	-	0,93



**Fig. 4.** Duckfoot castings for the cultivator spring teeth (made by the developed technology)

The ready duckfoot castings were subjected to a heat treatment process (austempering). To reduce the oxidation process at high temperature, the austenitising treatment was carried out in a protective atmosphere of argon.

Hardness after heat treatment, measured on the three finished castings of duckfoot, ranged between 36 and 40 HRC which, according to PN-EN 1564, has qualified this material as EN GJS 1200-2 [1].

# CASTING OF SUBSOILER COULTER

Subsoiler coulter operates in soil exposed to the conditions of tribological wear. The depth of soil cultivation reaches 80 cm. The technology used so far consists in punching and cutting of steel components, and then drilling, welding, grinding, and applying a protective anti-corrosion coating. A photograph of this tool operating directly in the soil during pre-sowing land cultivation is shown in Figure 5.



Fig. 5. A photograph of the welded subsoiler coulter
As a part of the ongoing work, a new innovative design of the cast subsoiler coulter was developed. A documentation was elaborated, adapting the design of the tool to the operating conditions and casting manufacturing technology. Illustrative models were prepared next, using the same design technique as for the design of the cultivator duckfoot castings. Figures 6 and 7 show models of the subsoiler coulter in version selected for trials.



Fig. 6. Virtual 3D model of subsoiler coulter made in Solid Works



**Fig. 7.** Pattern of subsoiler coulter made by RP on a 3D DI-MENSION 1200es printer

Based on the results of computer simulation, a technology for casting the subsoiler coulter was developed (Figure 8).



The performed computer simulation of mould filling and metal solidification process according to the developed technology revealed that:

- the use of two risers in exothermic sleeves ensures full feeding of the casting,
- the obtained final properties indicate that the casting has a ferritic structure,
- the tensile strength R<sub>m</sub> in the casting cross-section exceeds the value of 400 MPa, reaching in some areas 500 MPa and more,
- hardness ranges from 150 to 170 HB,
- elongation is from 16 to 19%,
- large variations of properties in the casting cross-section are due to variations in the wall thickness, and thus to a temperature gradient between the individual points of the casting [4-8],
- the applied heat treatment significantly changes the alloy properties, leading to their homogenisation in the casting cross-section [4-7].

From the cast iron of the composition given in Table 2, a pilot batch of subsoiler coulters was cast. A photograph of these castings is shown in Figure 9.

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Ductile	Chemical composition; wt.%										
iron	С	Si	Mn	Р	S	Mg	Ni	Мо	Cu		
nickel- molybdenum	3,85	2,90	0,61	0,050	0,010	0,080	1,50	0,47			



Fig. 9. Subsoiler coulters cast by the developed technology

The heat treatment process of the subsoiler coulters was performed in an LT ADI -350/1000 technological line using the following equipment:

- electric chamber furnace, type B4 ENL,
- salt bath, type WS-4/450 EL,
- washing and drying device, type WPSD-4EL.

Hardness after heat treatment, measured on the six finished castings of subsoiler coulters ranged between 39 and 42 HRC which, according to PN-EN 1564, has qualified this material as EN GJS 1200-2 [1].

Fig. 8. Casting technology

#### CONCLUSIONS

The investigation of the operating conditions and of the wear and tear behaviour of the cultivator duckfoot and subsoiler coulters allowed, using special computer programmes, for the design of these tools in a new geometry, better adjusted to the requirements of the casting technology.

The tests previously conducted on ADI enabled the selection of the best material for the designed new items, optimising at the same time the heat treatment parameters [2, 3, 11-14, 18-20].

The, developed through computer simulation, casting technologies for the manufacture of subsoiler coulter and cultivator duckfoot allowed making high-quality cast tools for the cultivation of agricultural land. Prototype castings of these tools were transferred to the operational testing and the results will be discussed in a publication to follow.

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#### ODLEWANE NARZĘDZIA ROLNICZE PRACUJĄCE W GLEBIE

S tr e sz c z e n i e. W pracy opisano nowe konstrukcje odlewanych narzędzi rolniczych pracujących w glebie. Wykorzystując dotychczasowe doświadczenia związane z wdrażaniem nowych lemieszy do pługów obracalnych i zagonowych wykonanych z żeliwa ADI, przystąpiono do opracowania konstrukcji i odpowiedniej technologii odlewania redlicy głębosza oraz gęsiostópki kultywatora. Odlewy te obrobiono cieplnie (hartowanie z przemianą izotermiczną) i przekazano do badań eksploatacyjnych. Opracowanie tych innowacyjnych narzędzi pod względem geometrii kształtu i doboru odpowiedniego tworzywa odlewniczego odpornego na szczególnie trudne warunki pracy pozwoliło zwiększyć ich funkcjonalność i trwałość eksploatacyjną.

Słowa kluczowe: stopy żelaza, żeliwo sferoidalne, ADI, symulacja komputerowa, narzędzia rolnicze.

#### Performance testing of cast agricultural tools operating in soil

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S u m m a r y. After extensive studies of materials and making from selected ADI grades the pilot subsoiler coulters and cultivator duckfoot castings, the performance tests were conducted on these elements. A methodology of the studies was developed, farms were selected to carry out the tests, and the results were examined. It was shown that the service life of both the subsoiler coulter and cultivator duckfoot made by the casting technology from properly selected material is much longer than the service life of the presently used steel tools forged and welded.

Key words: iron alloys, ductile iron, ADI, agricultural tools, performance tests.

#### **INTRODUCTION**

The aim of testing the castings operation was to verify the performance of the applied material and technology conversion in production of selected agricultural tools operating in soil [1-3,8,9,13-16,21,23].

From the alloys studied, a series of selected agricultural pilot cast tools for the soil treatment was made. The castings were subjected to a heat treatment, which in this case involved an austempering process [4-7, 10-12, 17, 18].

The ready pilot tools were undergoing pre-operational testing (mainly for tribological wear behaviour). The scope of the research included:

- selecting for performance tests the designed and manufactured parts of agricultural machinery for soil-working,
- selecting farms where reliable trials can be conducted,
- developing guidelines for the tribological test procedure,
- preparing appropriate forms which farmers are supposed to complete before taking the castings for trials,
- supervising the preliminary tests carried out under field conditions,
- collecting comments, observations and test results.

The object of the studies were innovative, prototype cast elements (duckfoot of the cultivator spring teeth and subsoiler coulters) made from the high-quality alloyed ductile iron after austempering treatment. Properly prepared for tests, these elements were given to farmers using specially designed Test Tool Commissioning Sheets. The sheet took into account the following data: type of the farm, type of the agricultural machinery selected for tests, number of items (tools) commissioned for testing, and date of the commissioning.

#### TEST CONDITIONS

In assessing the conditions of the conducted tribological tests, the stoniness of soil and its moisture content were determined.

The field soil stoniness was determined in accordance with PN - 90/R -55 003 "Test methods for agricultural machines" with division into the following classes:

- very low, up to 5 t/ha (up to 5 tonnes of stones per 1 hectare of the field area),
- low, 5 20 t/ha,
- medium, 20 50 t/ha,
- high, above 50t/ha.

The relative (expressed in weight units) soil humidity was determined in accordance with PN - 90 / R - 55 003, collecting field soil samples (250 g) to the sealed plastic bags. A properly selected batch of soil was taken from the bag , weighed on an electronic scale with an accuracy to the nearest 0.0002 g, and then dried in a drier at  $105^{\circ}$ C during 30 min. After drying, the batches of the soil were re-weighed. The relative humidity was determined from the following formula:

$$\mathbf{W}_{g} = \frac{m_{1} - m_{2}}{m_{2}}$$
 100 [%],

#### where:

m<sub>1</sub> - mass of soil from the examined field, m<sub>2</sub> - mass of soil from the examined field after drying.

#### THE WEAR AND TEAR CHARACTERISTICS OF CULTIVATOR DUCKFOOT

Cultivator duckfoot operates in soil during field work under the conditions of tribological wear. The cast duckfoot elements were subjected to performance tests. According to the assumptions made previously, the operating speed of a tractor-combined cultivator set was 5 to 8 km/h. The study was conducted on soils of Class III and IV, i.e. on medium-firm soils after cultivation with disc harrow. The soil stoniness on the farm, where the performance tests of cultivator duckfoot castings were conducted, was defined as low. The on-farm soil moisture content during the tests was approximately 7.4%, while the measured air humidity was 62.8% at a temperature of 11.4 °C.

The study involved eight pieces of the randomly selected duckfoot castings. In the period of October - November 2011, tests were conducted on the surface area of 15ha (150 000 m<sup>2</sup>). The operating depth of tools was 8 - 12 cm.

Figure 1 shows these elements mounted in a machine during the conducted tribological test.





**Fig. 1.** Duckfoot castings mounted on springs of the soil cultivating aggregate teeth (after the tribological field testing)

The farmer's own cultivating aggregate provided with the spring teeth ending in the tested duckfoot castings was operating in the soil prior to crop sowing. The tested duckfoot castings were fixed in the first row, most exposed to heavy abrasion wear.

After completing the preliminary tribological tests, all items were collected from the places where they were tested in accordance with the Test Tool Commissioning Sheets and under laboratory conditions the following final operations were performed:

- photographs of the worn-out parts were taken,
- castings were weighed to determine the final mass loss and wear rate under the conditions of the stochastically changing abrasive environment (soil),
- selected elements were scanned to allow an objective assessment of the degree of wear and the mode of wear (using images of the scanned area) observed on individual edges and possibly on the working surfaces.

In Figures 2 and 3 photographs are shown comparing the worn-out duckfoot castings after tribological tests with tools before the wear test.



**Fig. 2.** The appearance of duckfoot casting after (left) and before (right) the tribological field testing



**Fig. 3.** A comparison of duckfoot surface topography after (left) and before (right) the tribological field testing



Fig. 4. Graph illustrating the percent loss of weight in duckfoot casting per 1 ha of the cultivated land surface area (preliminary testing)



Fig. 5. (left) A photograph comparing the edge contour in duckfoot no. 10 worn out during the tribological test (the highest mass loss among all the tested specimens) with an outline of the CAD 3D model

**Fig. 6.** (right) A photograph comparing the edge contour in duckfoot no. 16 worn out during the tribological test (the lowest mass loss among all the tested specimens) with an outline of the CAD 3D model

As a primary indicator of the tribological wear rate, the percent loss in duckfoot weight per 1 ha of the cultivated land surface area was adopted. The results of the mass loss abrasive wear test are shown in Figure 4.

Figures 5 and 6 show the wear images of duckfoot castings, compared with their 3D CAD models made by the method of optical scanning using a GOM ATOS II scanner.

Comparing the scans of the duckfoot castings before and after the tribological tests, it was concluded that:

- there was an evenly balanced wear on the leading edge of the item and on the total duckfoot leading surface, running up to the mounting hole,
- duckfoot no. 10, with the greatest loss in mass, was significantly reduced in length, as shown in Figure 5,

- duckfoot no. 16, with the lowest degree of abrasive wear, revealed no significant signs of wear, besides a rounding off on the leading edge (Fig. 6),
- the maximum size of surface deviations in both the compared duckfoot castings was at the level of -4.74 mm.

### THE WEAR AND TEAR CHARACTERISTICS OF SUBSOILER COULTER

Subsoiler coulter operates in soil during field work under the conditions of tribological wear. The cast subsoiler coulters were subjected to performance tests. According to the previously-made assumptions, the operating speed of a tractor-three-tooth subsoiler set was 10-12 km/h. The study was conducted on soils of Class III and IV, i.e. on heavy clay soils, after cultivation with disc harrow. The soil stoniness on the farm, where the performance tests of subsoiler coulter castings were conducted, was defined as low. The on-farm soil moisture content during the tests was approximately 9.3%, while the measured air humidity was 73.4% at the temperature of 16.2 °C.

The study involved randomly selected subsoiler coulter specimens. In the period of October - November 2011, tests were conducted on the surface area of 7 ha (70 000  $m^2$ ). The operating depth of tools was 35 - 40 cm.

Figure 7 shows the subsoiler coulter operating in soil (tribological test).





**Fig. 7.** A photograph illustrating the operation of subsoiler coulter in soil (tribological test)

Figures 8 and 9 are photographs showing the appearance and surface topography of a cast subsoiler coulter before and after the tribological testing.





**Fig. 8.** The appearance of coulter before (left) and after (right) the tribological field testing



**Fig. 9.** A comparison of subsoiler coulter surface topography before (left) and after (right) the tribological field testing

Similar to the duckfoot case, as a primary indicator of the tribological wear rate, the percent loss in tool weight per 1 ha of the cultivated land surface area was adopted. The mass loss abrasive wear test results are shown in Figure 10.



**Fig. 10.** Graph illustrating the percent loss of weight per 1 ha of the cultivated land surface area in the new design of coulter (type 1) as compared with the original design (type 2) used in a three-tooth subsoiler made by BOMET

Figures 11 and 12 show the, made by the method of optical scanning using a GOM ATOS II scanner, wear

images of coulter castings before and after the tribological test.



**Fig. 11.** (left) A photograph comparing the scans of cast coulter before and after the tribological wear test with well visible leading surface and dimensional deviations

**Fig. 12.** (right) A photograph comparing the scans of cast coulter before and after the tribological wear test with well visible leading surface and dimensional deviations

Based on the compared scans of the coulter castings before and after the tribological tests, it was concluded that:

- there was an evenly balanced wear on the leading edge of the coulter point and a small degree of wear on the whole coulter leading surface,
- during tribological tests, a discontinuity in the casting structure was revealed, as evidenced by the scans,
- the maximum size of surface deviations in the compared scans of coulters before and after the tribological test was at a level of -1.6 mm, the deviations on the leading edge were at a level of -4.0 mm.

#### CONCLUSIONS

Summing up the results of the quality assessment and of the performance tests of tribological wear conducted on the designed and manufactured agricultural tools operating in soil, the following conclusions were drawn:

- Rockwell hardness of duckfoot and coulter parts cast from austempered ductile iron was approximately 40HRC, and thus was consistent with the technological guidelines,
- the preliminary tribological tests conducted under field conditions according to the developed methodology showed that:
  - a) in the cast cultivator duckfoot, the average weight loss per 1 ha of the surface area was 0.48%, and it was much lower than the weight loss reported for the same component made from the wearresistant steel, for which it amounted to about 1.87% - data published in the literature [19, 20],
  - a) for the cast subsoiler coulters, the weight loss per 1 ha of the surface area was 0.40%, and it was much lower than the weight loss reported for the tested original coulter welded from boron-containing steel, for which it amounted to about 0.87%,
- scanning of the tested working parts (duckfoot and coulter castings) for the wear and tear under field conditions showed no significant differences in the nature of wear and in the permanent deformation of the tested elements - only some minor changes in the surface and edge area have been observed,
- the scatter of these deviations was from 0 mm to -4.74 mm for duckfoot castings and from -1.60 mm to 1.5 mm for coulters,
- these values suggest a very moderate abrasive wear of the tested elements, and hence a correct choice of both the material and manufacturing technology,
- more extensive comparative studies to be carried out in 2012 are expected to make full verification of these statements.

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#### BADANIA EKSPLOATACYJNE ODLEWANYCH NARZĘDZI ROLNICZYCH PRACUJĄCYCH W GLEBIE

Streszczenie. Po przeprowadzeniu szerokich badań materiałowych i wykonaniu, z wytypowanych gatunków żeliwa ADI, odlewów eksperymentalnych redlic głębosza i gęsiostópek kultywatora, przystąpiono do badań eksploatacyjnych tych odlewów. Opracowano metodologię tych badań, wytypowano gospodarstwa rolne do ich przeprowadzenia i przeanalizowano uzyskane wyniki. Wykazano, że trwałość eksploatacyjna zarówno redlic głębosza, jak i gęsiostópek kultywatora wykonanych w technologii odlewniczej z odpowiednio dobranego tworzywa jest znacznie większa niż obecnie stosowanych stalowych narzędzi kutych i spawanych.

Słowa kluczowe: stopy żelaza, żeliwo sferoidalne, ADI, narzędzia rolnicze, badania eksploatacyjne.

### Testing ADI properties when used for cast agricultural tools operating in soil

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Summary. The paper discusses the influence of heat treatment parameters on selected properties of austempered ductile iron (ADI). The studies involved two grades of low-alloyed ductile iron: nickel-molybdenum and nickel-copper. The results of laboratory tests were used in the selection of material for cast agricultural tools operating in soil: subsoiler coulters and cultivator duckfoot.

Key words: iron alloys, ductile iron, ADI, mechanical properties, agricultural tools.

#### INTRODUCTION

Austempered ductile iron (ADI) is increasingly used for cast parts operating in different machines and equipment, including cast agricultural tools for soil cultivation [1-3, 9, 10, 14]. The problem in selecting the best type of this cast iron as regards the operational requirements of the tools is to obtain the mechanical/plastic properties relationship consistent with the operating conditions of a casting [4-8, 11-13, 20, 21]. The purpose of this study has been to identify the obtainable properties of ADI based on the heat treatment parameters (isothermal cooling temperature) [15-17]. The study involves low-alloyed ductile iron of nickel-molybdenum type and nickel-copper type used for the manufacture of cast subsoiler coulters and cultivator duckfoot, respectively.

#### CHOICE OF DUCTILE IRON CHEMICAL COMPOSITION

Austempered ductile iron was selected as a test material. As a base cast iron for further heat treatment, two grades of ductile iron were chosen. They differed in the type and content of the introduced alloying elements improving the hardenability of this material (nickel, copper, molybdenum) [12,14,18,19]:

- first low-alloyed nickel-molybdenum ductile iron containing about 1.6 wt.% nickel and about 0.4 wt.% molybdenum,
- second low-alloyed nickel-copper ductile iron with nickel content of about 1.9 wt.% and copper in an amount of about 0.9 wt.%.

#### MELTING PROCEDURE

Melting was carried out in a PIT 150 medium frequency induction furnace made by ZAM Kęty with a 150 kg metallic charge capacity crucible and neutral lining. The following stock was used as charge materials: foundry pig iron, steel scrap, FeMn82 ferromanganese, FeSi75 ferrosilicon, metallic nickel, electrolytic copper, FeMo60 ferromolybdenum.

The spheroidising treatment and inoculation were performed by the technique of elastic wire, using two wires: the first one containing an FeSiMg17 magnesium master alloy (1.5% respective of molten metal weight), and the second one containing an FeSi75T inoculant (1% respective of molten metal weight). The treatments were performed in a slender ladle at 1400°C.

From the melts, samples were taken for laboratory testing and prototype utility castings were made (pilot agricultural tools for soil cultivation).

Samples for chemical analysis were poured in metal moulds (copper dies), pilot castings and samples for other laboratory tests were poured in bentonite sand moulds.

#### CHEMICAL ANALYSIS

Chemical analysis of melts was performed by emission spectrometry on a POLYVAC 2000 (Hilger Co., UK) apparatus in accordance with the certified test procedures developed by the Foundry Research Institute in Cracow. The results are summarised in Table 1.

tilo	am	Chen	Chemical composition; wt.%									
	iron	С	Si	Mn	Р	S	Mg	Ni	Мо	Cu		
lalain	molybdenum	3,85	2,90	0,61	0,050	0,010	0,080	1,50	0,47	-		
-loloin	copper	3,60	2,45	0,32	0,035	0,020	0,065	1,90	-	0,93		

Table 1. Chemical analysis of melts

#### METALLOGRAPHIC EXAMINATIONS OF AS-CAST SPECIMENS

Metallographic examinations were performed in accordance with the procedure specified in a TBS/P/002/02: 2008 Instruction Manual. Graphite microstructure was determined comparing the microstructure of unetched specimens with reference standards shown in PN-EN ISO 945:1999. Microstructure of the metallic matrix was examined comparing the microstructure of etched specimens with reference standards shown in PN-75/H-04661. Polished sections were etched with Mi1Fe reagent (4% nital) according to PN-61/H-04503.

Microscopic observations and photographs were taken with an AXIO OBSERVER Z1M metallographic microscope.

The results of metallographic observations are summarised in Table 2, and examples of microstructure images are shown in Figure 1.

**Table 2.** The results of metallographic observations conducted on as-cast specimens

Ductile iron	Graphite microstructure	Metallic matrix microstructure
nickel- molybdenum	80% VI6 + 20% V6	P45-Pd0,5
nickel-copper	90% VI5 +10% V5	Pf1-P96-Pd1,0





**Fig. 1.** Microstructure of nickel-molybdenum (up) and nickelcopper (down) ductile iron, sections etched with MilFe

#### TESTING AS-CAST IRON MECHANICAL PROPERTIES

Testing of mechanical properties included hardness measurements and static tensile test at ambient temperature. Hardness was measured on the Rockwell C scale in accordance with PN-EN ISO 6508-1:2007. The tensile test was performed according to PN-EN 10002-1:2004 using an EU-20 testing machine made by FEB Werkstoffprufmaschinen Leipzig, Germany. The stress increase rate during the test was 1.59 MPa/s, the loading force was 1471 N, and the nominal load operation time was 4 sec. The obtained results of the mechanical tests are summarised in Table 3.

Table	3.	The	results	of	mech	ianica	l tests	carried	out	on
as-cast s	spec	eimer	15							

	Results of mechanical tests								
Ductile iron	HBS 5/750 [-]	R <sub>m</sub> [MPa]	R <sub>p0,2</sub> [MPa]	A [%]	Z [%]				
nickel- molybdenum	360	936	657	1,8	0,4				
nickel-copper	257	764	479	2,5	2,0				

#### HEAT TREATMENT

Specimens were undergoing the heat treatment in a Multitherm N41/M Nabertherm furnace (Germany) with an air-tight retort and inert gas (argon) protective atmosphere to avoid surface decarburising.

In this furnace, the operations of austenitising treatment were carried out, keeping the same regime for all the batches:

- heating with furnace to a temperature of 900°C,

- holding at this temperature for 2 h.

The isothermal cooling treatment was carried out in a PEW-2 electric bath-type furnace using salt bath (a mixture of potassium nitrate and sodium nitrite). The salt bath temperature and the isothermal cooling times were as follows:

- for nickel-molybdenum ductile iron specimens:
  - 370 °C / 2 h cycle "A1",
  - 320 °C / 2 h cycle "B1",
  - 270 °C / 3 h cycle "C1",
- for nickel-copper ductile iron specimens:
  - 375 °C / 2,5 h cycle "A2",
  - 330 °C / 2,5 h cycle "B2",
  - 270 °C / 3 h cycle "C2",

After heat treatment, specimens from each cycle were subjected to laboratory testing.

#### METALLOGRAPHIC EXAMINATIONS OF HEAT TREATED SPECIMENS

Metallographic examinations of the austempered ductile iron specimens were performed in accordance with the procedure specified in a TBS/P/002/02:2011 Instruction Manual.

Microscopic observations and photographs were taken with an Axio OBSERVER Z1M metallographic microscope, metallographic sections were prepared in accordance with the procedure specified in a TBM/001 Instruction Manual.

To reveal the microstructure of the metallic matrix, the metallographic sections were etched in modified BM reagent of the following chemical composition: 100 ml stock solution (5 parts by vol. H<sub>2</sub>O, 1 part by vol. concentrated HCl), 2 g NH4Fe • HF, 1 g K<sub>2</sub>S<sub>2</sub>O<sub>5</sub>. This reagent did not colour the austenite and carbides, but coloured bainite and tempered martensite in brown and martensite in blue. Sometimes fine martensite needles were not coloured in blue but in light brown, and then in the microstructure evaluation their morphology should be taken into account.

Microstructures of the examined specimens of ductile iron after heat treatment are shown in Figures 2 - 7, while descriptions of the structure are compared in Table 4.

Table	4.	The results	s of meta	llographic	observations	con-
ducted c	on he	eat treated	specime	ns		

Ductile iron					
Type Heat treatment cycle		Graphite microstructure	Metallic matrix microstructure		
	A1	80% VI6 + 20% V6	B + M (about 2%)		
el- lenum	B1	80% VI6 + 20% V6	B + M (about 2%)		
1. nick molyb	C1	80% VI6 + 20% V6	В		
ar	A2	90% VI5 +10% V5	B + M (about 15%) + A (traces)		
el-coppe	B2	90% VI5 +10% V5	B + M (traces, <1%) + A (traces)		
2. nick	C2	90% VI5 +10% V5	B +F (traces) +A (traces)		
B – bai	nite (ausferi	rite) M – martensite	on boundaries of eutectic		

B – bainite (ausferrite), M – martensite on boundaries of eutectic cells, F – ferrite, A – retained austenite



**Fig. 2.** Microstructure of specimen A1, metallic matrix, etched section

**Fig. 3.** Microstructure of specimen B1, metallic matrix, etched section



**Fig. 4.** Microstructure of specimen C1, metallic matrix, etched section



**Fig. 5.** Microstructure of specimen A2, metallic matrix, etched section



**Fig. 6.** Microstructure of specimen B2, metallic matrix, etched section



**Fig. 7.** Microstructure of specimen C2, metallic matrix, etched section

5.

6.

#### TESTING THE MECHANICAL PROPERTIES OF HEAT-TREATED DUCTILE IRON

As in the case of as-cast condition, testing of mechanical properties included the measurement of hardness and static tensile test at ambient temperature, as well as Charpy impact test at ambient temperature conducted in accordance with PN-EN 10045-1:2007. Hardness was measured on the Rockwell C scale in accordance with PN-EN ISO 6508-1:2007. The tensile test was performed in the same manner as for the as-cast condition.

The results of mechanical tests obtained on heat-treated specimens are compared in Table 5.

Table	5.	The	results	of	mec	hani	ical	tests	carried	out	on
heat-trea	ated	spec	cimens								

Ductile iron		Results of mechanical tests						
Туре	Heat treatment cycle	HRC [-]	R <sub>m</sub> [MPa]	R <sub>p0,2</sub> [MPa]	A [%]	Z [%]	KCV [J/ cm <sup>2</sup> ]	
um	A1	28	875	460	6,2	6,9	9,6	
ckel- /bden	B1	38	1161	512	3,0	5,2	8,3	
1. ni moly	C1	44	1275	687	1,5	1,9	7,3	
	A2	27	950	575	8,2	7,1	9,9	
ckel- er	B2	36	1168	827	5,6	5,5	8,6	
2. ni copț	C2	43	1485	1133	2,4	2,4	7,9	

#### CONCLUSIONS

Tests conducted on austempered ductile iron helped to quantify the effect of alloy cooling temperature on the selected mechanical and plastic properties of ADI, obtained under given conditions.

Comparing the results obtained for nickel-copper and nickel-molybdenum cast irons it was found that, at comparable strength parameters, the former of these alloys offers slightly higher plastic properties than the latter one.

In the case of nickel-copper ductile iron, under comparable heat treatment parameters, higher mechanical properties were obtained than in the case of nickel-molybdenum cast iron.

The collected information enabled choosing the type of alloy and heat treatment parameters best for the production of cast agricultural tools operating in soil. Consequently, nickel-molybdenum cast iron was used for subsoiler coulters and nickel-copper cast iron was used for cultivator duckfoot. The design, technology and operational tests performed on these castings will be described in subsequent articles.

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#### BADANIA MATERIAŁOWE ŻELIWA ADI PRZEZNACZONEGO NA ODLEWY NARZĘDZI ROLNICZYCH PRACUJĄCYCH W GLEBIE

S tr e s z c z e n i e. W pracy omówiono wpływ parametrów obróbki cieplnej na wybrane właściwości żeliwa sferoidalnego hartowanego z przemianą izotermiczną. Przedmiotem badań były dwa rodzaje sferoidalnego żeliwa niskostopowego: niklowo-molibdenowe i niklowo miedziowe. Uzyskane rezultaty badań laboratoryjnych wykorzystane zostały przy doborze tworzywa na odlewy narzędzi rolniczych pracujących w glebie: redlice głębosza i gęsiostópki kultywatora.

Słowa kluczowe: stopy żelaza, żeliwo sferoidalne, ADI, właściwości mechaniczne, narzędzia rolnicze.

#### Modelling of the robot sensor system

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S u m m a r y. Robot sensor operation is presented as the processing of some grammar of attributes. Words defined in the grammar are signals from the sensing elements of the sensor system. Processing of these words is executed by a translator modelled by an automaton with LIFO memory. This method of processing robot sensor signals enables the design of the system software. The software structure is independent of system application. The proposed method of organization of robot sensor operation software is also useful for the automation of its designing.

Key words: grammar of attributes, sensor, translator

#### INTRODUCTION

Contemporary robots are distinguished by an extensive sensor system [2,8,16,17]. The number of signals from sensing elements is constantly growing, and their processing at different stages of the robot control process requires the application of advanced methods. Measurement sequences are set from the series of signals coming from various sensing elements. Depending on the needs, these sequences can be set from several, a dozen or so, or even several dozen signals arranged in an appropriate order [3,11,12]. The type of a measurement sequenced needed for the execution of the robot control process is determined by the control system. The response of the sensor processing system are directives sent to the robot control system [4,14].

#### STRUCTURE OF THE ROBOT SENSOR SYSTEM

The robot sensor operation system can be incorporated in the robot's control structure, in a manner as shown in Fig.1 [10,13].

The process of sensor system operation is executed at the stages of acquiring, processing and transmitting of information [6,7]. As a translator, it processes the words of some input language (sequences of signals from sensing elements) into the words of the output language (sequences of directives to the control system) [9]. The structure of such a translator is shown in Fig. 2.

The translator can be realized in the form of an automation with LIFO memory [1,5]. The functioning of the translator is determined by the grammar of the input language.



Fig. 1. Robot scheme structure



Fig. 2. Schematic diagram of the translator operating the robot sensor system

#### THE GRAMMATICAL MODEL OF THE SENSOR OPERATION SYSTEM

The grammar of the translator's input language is defined by setting the rules of morphological analysis [5,15]. The process of morphological analysis during processing of measurement signals sequences is controlled by the automaton based on the initial symbol provided by the control system. The initial symbol determines which of the measurement sequences is to be executed.

If the readings of all sensing elements are red out in the sequence, then the translator's input word will have a fixed syntactic structure. The input language grammar is at that case relatively simple. The rules of the morphological analysis of this grammar, as expressed in Backus-Naur's notation, are as follows:

$$\langle \text{init} \rangle \rightarrow \text{INTERRUPTION} \langle A \rangle$$
,  
 $\langle A \rangle \rightarrow \text{SENSOR} 1 \langle B \rangle$ ,  
 $\langle B \rangle \rightarrow \text{SENSOR} 2 \langle C \rangle$ ,  
 $\vdots$   
 $\langle Z \rangle \rightarrow \text{SENSOR} n$ ,

where: the brackets <,> denote auxiliary grammar symbols; <init>– initial symbol defining the measurement sequence; SENSOR *1*, SENSOR *2*, ... SENSOR *n* – basic grammar symbols, which input words, or sensing element signals correspond to; the first rule defines the method of initiating the operation – this can be clock interrupt, INTERRUPTION.

The sensor system operation process can form a multi-level system of external interrupts, and then the mode of processing depends on which interrupt will occur first, or which has a higher priority. The morphological analysis rules for this case have the following form (e.g. for n external interrupts of equal priorities):

 $\langle \text{init} \rangle \rightarrow \text{INTERRUPTION}_1 \langle A_1 \rangle | \text{INTERRUPTION}_2 \langle A_2 \rangle | \text{INTERRUPTION}_3 \langle A_3 \rangle,$ 

|...|INTERRUPTIONi<Ai>|...|INTERRUPTIONn <An>,: $<Ai> \to SENSORi1 <B>,$  $<Bi> \to SENSORi2 <C>,$ : $<Zi> \to SENSORik,$ :

where: in the first morphological analysis rule, the methasymbol | denotes the logical operation "OR"; n – number of interrupts; k – number of measured quantities for the *i*-th external interrupt.

In the presented grammar, interrupts may either have an equal priority or be ordered according to descending priority.

In order that the morphological analysis rules describe the translator, it is necessary to supplement them with operation symbols – procedures, which may perform various processing functions and will ultimately formulate translator output words [5,15]. In the control system, operation symbols should be executed immediately after appearing at the output of the translator-modelling automaton, thus the software is built as a translator.

The morphological analysis rules of the sensor operation system interpreter, for a simpler case, are as follows:

 $\langle init \rangle \rightarrow INTERRUPTION \{readout\} \{process0\} \\ \langle A \rangle \{result\} \{output\} \end{cases}$ 

$$\langle A \rangle \rightarrow SENSOR1 \{ process1 \} \langle B \rangle$$
  
 $\langle B \rangle \rightarrow SENSOR2 \{ process2 \} \langle C \rangle$   
 $\vdots$   
 $\langle Z \rangle \rightarrow SENSORn \{ processn \}$ 

For a system with multiple interrupts, operation symbols are analogous.

The operation symbols have the following meanings:

{readout} – analyzes the interrupt priority and initializes the readout of sensing element readings, and orders them at the automaton's input (for the case with multiple interrupts, the automaton input configuration depends on which interrupt is operated in a given computation cycle);

{process0} – tests the initial conditions;

{process*i*} – tests the readout value of the *i*-th sensing element;

{result} – determines the output directives based on the result of computation carried out;

{output} – relays directives defined by the operation symbol {result} to the interpreter's output.

With the practical implementation of the interpreter, the morphological analysis rules set out above are developed as attribute grammar morphological analysis rules [9]. The basic grammar symbols SENSORi have one attribute each, whose value is equal to the measured quantity. The initial symbol <init> has attributes, whose values are equal to initial values for a given computation cycle. For the case of multiple external interrupts, the basic symbol INTERRUPTION has a single interruptidentifying attribute, when the identification is hardwareexecuted. In the case of the software interrupt identification, the INTERRUPTION symbol has no attribute, but the operation symbol {interrupt definition}additionally occurring in the rule immediately after the INT symbol has one. The remaining grammar symbols have several attributes each, which take on different values. Very often, symbol attributes at the left-hand side of the symbol  $\rightarrow$  can be used when selecting the rule in the course of conducting morphological analysis.

Symbol attributes and inherited and synthesized. The values of inherited attributes are obtained by simple substitution. The values of synthesized attributes are obtained as a result of performing operations being the contents of operation symbol procedures. The arguments of these operations are the inherited attributes of a given operation symbol. Symbol attributes will be denoted as indexes.

As an example, let us consider the measurement sequence grammar, where two parameters are measured and three directives are determined for the robot control system. The morphological analysis rules are as follows (we assume here a single clock interrupt):



Fig. 3. Examples of LIFO memory symbols

The rules of attribute computation, as given in the grammar, are substitution operators. The grammar symbol attributes are as follows:

$$\begin{split} & \{\text{output}\}_{a,b,c} - \text{inherited } a,b,c, \\ & \{\text{result}\}_{a,b,c,d,e,f,g} - \text{inherited } a,b,c,d, \text{ synthesized } e,f,g, \\ & \{\text{process } 0\}_{a,b,c,d} - \text{inherited } a,b,c; \text{ synthesized } d, \\ & \{\text{process } 1\}_{a,b,c} - \text{inherited } a,b; \text{ synthesized } c, \\ & \{\text{process } 2\}_{a,b,c} - \text{inherited } a,b; \text{ synthesized } c, \\ & \{\alpha >_{a,b} - \text{inherited } a, \text{ synthesized } b, \\ & <\beta >_{a,b} - \text{inherited } a, \text{ synthesized } b. \end{split}$$

The sense of the division of attributes into inherited and synthesized is explained in Fig. 3, where the structures of several grammar symbols are shown.

In the attribute grammar of a system with multiple hardware-defined external interrupts, the operation symbol {readout} has a single attribute inherited from the INT symbol. The respective morphological analysis rule has the following form:

 $\langle \text{init} \rangle_{a,b,c} \rightarrow \text{INTERRUPTION}_{d} \{\text{readout}\}_{e} \{\text{process}0\}$  $f_{g,h,i} \langle A \rangle_{j,k} \dots$  $\dots e \leftarrow d; \dots$ 

For the software interrupt definition, the morphological analysis rule is as follows:

The attribute of the symbol {interrupt definition} is synthesized.



Fig. 4. Examples of execution of the sensor operation system attribute grammar rule

The attribute grammar is used for the construction of an attribute automaton performing the functions of an interpreter [1]. Such an automaton operates with grammar symbols based on its own control table. For storing grammar symbols, LIFO memory is used. A grammar symbol stored in the automaton's LIFO memory consists of a symbol description and a set of fields designed for storing attribute values. The fields of each symbol are memory words available for the recording and readout of information at the time when that symbol is contained in the memory. In the case of inherited attributes, the value of an attribute is stored in a respective field, and in the case of synthesized attributes, the field of an attribute stores its address, where the attribute value is written (the place of attribute value storage is the field of another symbol).

The automaton performs operations on the contents of the LIFO memory based on the top symbol and the current input symbol, following the morphological analysis rules. Operations performed on the LIFO memory contents are as follows:

- remove the symbol occurring at the top of the memory is eliminated;
- replace the top symbol in the memory is replaced with a sequence of symbols being the arguments of this operation.

The following operations are performed on the automaton's input:

move – proceeds to the analysis of the next input symbol;

hold – the current symbol at the input does not change.
 A single operation is performed on the automaton's output:

 issue – calling out the command to carry out the procedure described by the operation symbol.

An illustration of carrying out the operation by the attribute automaton for a selected morphological analysis rule for a sample grammar is shown in Fig. 4.

#### CONCLUSIONS

The theory of syntactic analysis and translation is an effective method of formalizing the process of designing software for robot sensor operation systems. Software in the form of an interpreter is distinguished by the simplicity and logic of organization, and its structure is independent of the specific designation of the system concerned. Thus, it is possible to introduce the teaching module in a simple manner in the form of a grammar rule generator. The proposed method of organization of robot sensor system operating software may also be useful in the automation of its design.

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#### MODELOWANIE SYSTEMU SENSORYKI ROBOTA

Streszczenie. Przedstawiono działanie układu sensorycznego robota jako przetwarzanie pewnej atrybutowej gramatyki. Słowa zdefiniowane w gramatyce są sygnałami z czujników układu sensorycznego. Przetwarzanie tych słów jest wykonywane przez translator modelowany przez automat z pamięcią LIFO. Ten sposób przetwarzania sygnałów czujników umożliwia projektowanie oprogramowania systemu. Struktura oprogramowania jest niezależna od zastosowanego systemu. Proponowana metoda organizacji oprogramowania systemu sensorycznego robota jest również przydatna w automatyzacji jego projektowania.

Słowa kluczowe: roboty, modelowanie, rozbiór gramatyczny, translator

### The quality of the mixing process depending on selected technical parameters

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Summary. Homogeneity is a system, in which particles of all raw materials show constant concentration, in random samples of a mix with defined sizes. It aims at achieving products of desired properties. The aim of the conducted research was to determine the influence of rotational speed of the stirrer and the type of raw material on homogeneity of the mixing process. The scope of research included the assessment of the influence of various rotational speeds of the stirrer on the quality of mixing in relation to the type of a raw material. In order to select the optimal rotational speed of the mixer the research was carried out at 3 different rotational speeds, i.e.: 80, 100 and 120 rpm for commeal used as the test raw material. Next, tests for different raw materials at a defined rotational speed were conducted. The research was carried out during a particular time of mixing, namely 5 minutes. The research was conducted in a single-shaft horizontal mixer with a vane working element. The size of particles of the mixed raw material influences the quality of the mixing process. The type of the mixed raw material influences the quality of mixing and particularly its physical properties. The level of CV while mixing cracked wheat indicates insufficient mixing of the raw material. Time of mixing should be lengthened. The results achieved from the research on the assessment of the influence of selected mixing parameters suggest that the research should be extended and take into account various mixing times.

Key words: mixing, micro-tracers, feed quality.

#### INTRODUCTION

In production processes the stage of mixing is one of the most important in the technological process. The aim of mixing is achieving a homogenous, as far as physical properties are concerned, mix of two or more ingredients. The measurement of quality is the degree of homogeneity of the final product. Homogeneity is a system, in which particles of all raw materials show constant concentration, in random samples of a mix which have defined sizes [12]. It aims at achieving products of desired properties. Out of many important factors which influence the quality of the mixing process, the characteristics of materials for mixing should be mentioned. It is the easiest to mix ingredients which have the same size of particles, regardless of the raw material used, but maintaining the properties of the grain material in each of the raw materials, i.e. without excessive grinding [3,1]. This kind of excessive grinding has, in many ways, a negative influence, e.g. in technology - excessive dusting, as well as nutritional reasons. With different sizes of particles, bigger grains while mixing are located in the upper part of the system, and smaller grains in the lower part of the mixer. While mixing, when we deal with a material of various densities, secondary segregation may take place [9]. However, when the proportion of density of heavier material to the density of lighter materials is lower than three, then the influence of sizes of grains predominates over the influence of the difference in density [5]. The disordered state can be achieved only in an ideal system, when the ingredients of the mix do not differ or differ only in properties which are insignificant to the process. The ingredient with the biggest percentage share in the mix plays a dominant role in the process because it displaces other smaller ingredients from the mix. The quality of mixing is also influenced by the shape of grains [8,10,14]. Round and smooth grains move easier than grains with irregular shapes or grains with sharp edges. For the purposes of mixing, mixers are used of different constructions, configurations of stirrers and sizes, depending on the scale of the industry, the type of produced fodder, the precision of ingredient distribution [2,15]. The main features, which should characterise mixers, are the shortest possible time of operation to achieve the appropriate state, the minimum consumption of energy, and ensuring the staff the simplicity of operation and availability of replacement parts [4,7,16].

A very important aspect, however, not only of the process of mixing itself, is low cost of purchasing and utilising the machine. The correct exploitation of machines has a big influence on the process of mixing, the final product, efficiency and quality. Apart from the basic aspects, i.e. lubricants in wheelworks, cleanliness of the inside, the control system and precision of functioning of the system which feeds the raw material should also be tested. Before using a new machine it should be tested because time and the final quality of product is influenced not only by the technical condition, but also by the scale of production, the order of added ingredients, and the placement in a technological line [6,11,13,17].

The aim of the conducted research was to determine the influence of rotational speed of the stirrer and the type of raw material on homogeneity of the mixing process.

#### MATERIAL AND METHODOLOGY

The scope of research included the assessment of the influence of various rotational speeds of the stirrer on the quality of mixing in relation to the type of raw material. The research was conducted on sweetcorn extrudate, wheat extrudate and cracked wheat. In order to select the optimal rotational speed of the mixer, the research was carried out at 3 different rotational speeds, i.e.: 80, 100 and 120 rpm for cornmeal used as the test raw material. Next, tests for different raw materials at a defined rotational speed were conducted. The research was carried out during a particular time of mixing, namely 5 minutes. The research was conducted in a single-shaft horizontal mixer with a vane working element.

The assessment of the quality of mixing was made on the basis of ASAE Standard (No.S303) with the use of micro-indicators. The coefficient of variation CV for particular samples was calculated from the following formula:

$$CV = \frac{\delta}{n} \cdot 100 \%$$

 $\delta$  - standard deviation,

n – average.

The micro-indicator MICROTRACER <sup>™</sup> F- BLUE was used as a tracer, using 50 grams per one ton of mix. In one gram of the micro-indicator there are 25000 pieces. Such an amount caused, that with 100% homogeneity

	6	7	8	9	10	
ingredients	х	х	х	х	х	
charge	-					
-	х	х	х	х	х	
	1	2	3	4	5	

Fig. 1. Points, were the samples were taken for the research

in a sample weighing 80 g taken from the mix there should be 100 pieces of the micro-indicator. Next, 80 g samples taken to define the level of mixing were separated in a machine designated for abstracting micro-indicators - type Rotary Detector, model BL-89, series XO-7. The diagram of points where the samples were taken from the mixer is presented in Fig.1.

An essential parameter of the mixing process is also the level of filling the chute. For selected raw materials, the identical level of filling the chute was established at 75%. As a result of different bulk densities of the raw materials, the portions of the raw materials which underwent mixing differed but the same level of filling the mixer chute was maintained. Bulk density of the tested raw materials, which predominated the mass of the mixed raw materials, is presented in Table 1.

Table 1. Bulk densities o	f the tested rav	/ materials
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	Bulk density [kg×m <sup>-3</sup> ]			
Raw material	Fraction 0-1mm	Fraction 1-2.5mm	Fraction over 2.5mm	
Sweetcorn extrudate	185	82	62	
Wheat extrudate	287	214	185	
Cracked wheat	519	642	695	

#### **RESULTS AND DISCUSSION**

Results of the research of homogeneity of mixing at different rotational speeds are presented in Table 2. After calculating the amount of micro-indicators in particular samples, the standard deviation and variation coefficient CV were defined on the basis of which homogeneity of mixing was assessed.

**Table 2.** The amount of micro-indicators in samples, in relation to the speed of the stirrer for fragmented sweetcorn extrudate.

	Trial	80 rpm	100 rpm	120 rpm	
	1	93	93	110	
	2	109	124	136	
	3	112	126	141	
	4	103	102	102	
	5	106	114	100	
	6	131	125	109	
	7	125	119	128	
	8	100	121	142	
	9	110	118	111	
10	10	134	106	101	
	Mean	112.3	114.8	118	
Standard deviation		13.532	11.043	16.971	
	CV	12.05	9.6196	14.382	

While assessing the level of mixing of raw materials at different rotational speeds of the stirrer it can be stated that the level depends on rotational speed. For the same conditions of mixing sweetcorn extrudate at the rotational speed of 100 rpm, the highest level of mixing was achieved. When we make an assessment from the point of view of efficiency of the mixing process, we should aim at the shortest possible time of mixing, which indirectly influences the energy consumption of the process. Establishing appropriate rotational speeds and defining the minimal mixing time influence the final efficiency of the mixing process.

As a result of assessing the quality of mixing after preliminary research, for further analyses one optimal mixing speed was adopted at 100 rpm.

The diagram below presents the relation of the mixing process for selected raw materials with the rotational speed 100 rpm and mixing time 300 seconds.

When analysing the diagram of homogeneity of mixing of tested raw materials, it can be stated that the best effect was achieved while using sweetcorn extrudate with particle sizes ranging from 1 to 2.5 mm. High values of the coefficient of variation were achieved for the fraction with particles over 2.5 mm. In case of sweetcorn extrudate, the coefficient was over 35%, which accounts for inadequate mixing of the raw material. When assessing the quality of mixing according to European standards, in which it is assumed that adequate mixing takes place when the coefficient of variation for premixes is over 10%, and for complete mixes below 15%, it can be stated that a product with particles bigger than 2.5 mm was not mixed and technical parameters of the mixer should be changed or mixing time lengthened. However, in case of raw materials whose particle size was below 2.5 mm, homogeneity of mixing was adequate for wheat and sweetcorn extrudates. For cracked wheat homogeneity of mixing was inadequate, regardless of particle sizes.

#### CONCLUSIONS

On the basis of the conducted research the following conclusions were formulated:

- 1. The rotational speed of the stirrer influences homogeneity of mixing.
- 2. The size of particles of the mixed raw material influences the quality of the mixing process. Within the scope of tested parameters, bigger particles mix in a more difficult way and time of mixing should be changed.
- 3. The type of the mixed raw material influences the quality of mixing and particularly its physical properties. The level of CV while mixing cracked wheat indicates insufficient mixing of the raw material. Time of mixing should be lengthened.
- 4. The results achieved from the research on the assessment of the influence of selected mixing parameters suggest that the research should be extended and take into account various mixing times.

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Fig. 2. Coefficient of variation by the type of the used raw material.

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#### JAKOŚĆ PROCESU MIESZANIA W ZALEŻNOŚCI OD WYBRANYCH PARAMETRÓW TECHNICZNYCH

Streszczenie. Miernikiem jakości jest stopień jednorodności produktu finalnego. Za jednorodność uważa się układ, w którym cząstki wszystkich surowców wykazują stałą koncentracje, w dowolnych, ale o określonych wielkościach, próbach mieszanki. Celem prowadzonych badań było określenie wpływu prędkości obrotowej mieszadła oraz rodzaju surowca na homogenność procesu mieszania. Zakres badań obejmował ocenę wpływu różnych prędkości obrotowych mieszadła na jakości mieszania w zależności od rodzaju mieszanego surowca. Badania przeprowadzono na ekstrudacie kukurydzy, pszenicy oraz śrucie pszennej. W celu wyboru optymalnej prędkości obrotowej mieszarki przeprowadzono badania dla 3 różnych prędkości obrotowych t.j.: 80,100 i 120 obr./min. dla kaszki kukurydzianej jako surowca testowego. Następnie prowadzono badania dla różnych surowców przy określonej prędkości obrotowej. Badania przeprowadzono dla jednego czasu mieszania wynoszącego 5 minut. Badania wykonano na jedno-wałowej mieszarce poziomej z łopatkowym elementem roboczym. Opierając się na uzyskanych wynikach można stwierdzić, że wielkość cząsteczek mieszanego surowca wpływa na jakość procesu mieszania. Na jakość mieszania wpływa rodzaj mieszanego surowca, a w szczególności jego właściwości fizyczne. Poziom CV przy mieszaniu śruty pszennej wskazuje na niedostateczne wymieszanie surowca. Należałoby wydłużyć czas mieszania. Otrzymane wyniki z badań nad oceną wpływu wybranych parametrów mieszania sugerują poszerzenie badań o różny czas mieszania.

Słowa kluczowe: mieszanie, mikrowskaźniki, jakość.

# An algorithm for identification of the relaxation spectrum of viscoelastic materials from discrete-time stress relaxation noise data

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Summary. New algorithm of the least-squares approximation of the spectrum of relaxation frequencies by the finite series of Hermite functions using discrete-time noise corrupted measurements of relaxation modulus obtained in stress relaxation test has been proposed. Since the problem of relaxation spectrum identification is ill-posed, the inverse problem of Tikhonov regularization with guaranteed model approximation is used to achieve the stability of the scheme. The linear convergence of approximations generated by the scheme is proved for noise measurements. It is also indicated that the accuracy of the spectrum approximation depends both on measurement noises and regularization parameter and on the proper selection of time-scale parameter of the basis functions. The validity and effectiveness of the method is demonstrated using simulated data of Gaussian relaxation spectrum. Applying the proposed scheme, the relaxation spectrum of an unconfined cylindrical specimen of the beet sugar root is determined.

Key words: relaxation spectrum, identification algorithm, regularization, Hermite functions

#### INTRODUCTION

The selection of an appropriate mathematical representation is of central importance in the analysis of a physical system. Essentially, the choice of respective model depends on two criteria: the particular characteristics to be abstracted and our ability to specify the representation quantitatively. System identification deals with the problem of building mathematical models of systems (processes) based on observed data. In order to find such a model, which will describe well the system (process), an appropriate identification method must be derived [16].

In rheology it is assumed that the relaxation modulus G(t) has the following representation [5,18]:

$$G(t) = \int_{0}^{\infty} H(v) e^{-tv} dv, \qquad (1)$$

where: H(v) His the spectrum of relaxation frequencies  $v \ge 0$ .

Since, as it is well-known, for many materials the long-term modulus  $\lim_{t\to\infty} G(t) = G_{\infty} > 0$  (see [18,21], as well as the Example 3 below), instead of the classical equation (1), it is convenient to consider the following 'more-realistic' augmented material description:

$$\overline{G}(t) = \int_{0}^{\infty} H(v)e^{-tv}dv + G_{\infty} = G(t) + G_{\infty}.$$
(2)

The spectrum is recovered from discrete-time measurements  $\overline{G}(t_i) = G(t_i) + z(t_i)$ , i=1,...,N, of relaxation modulus obtained in stress relaxation test. Here  $z(t_i)$  is additive measurement noise. A complication for determining the relaxation spectrum is, that this problem is undetermined and ill-conditioned in the Hadamard sense [11,21]. Due to the noise or truncation of the experimental data, many models may fit the relaxation modulus experimental data adequately, but small errors in the data may lead to large changes in the determined models. The mathematical difficulties can be overcome by synthesis of an appropriate identification algorithm. In the paper [22] the following model of the spectrum H(v) is taken:

$$H_{K}(\nu) = \sum_{k=0}^{K-1} g_{k} h_{k}(\nu), \qquad (3)$$

where:  $g_k$  are constants and  $h_k(v)$  are Hermite functions:

$$h_k(\nu) = \frac{\sqrt{\alpha}}{\sqrt{2^k k!} \sqrt[4]{\pi}} e^{-(\alpha \nu)^2/2} P_k(\alpha \nu), \quad k = 0, 1, \dots,$$
(4)

with: Hermite polynomial  $P_k(x)$  defined by [22; eqs. (3), (4)]. Here notation [22; eqs. (3), (4)] is used for the

equations (3) and (4) in the paper [22]. The square index [12,14,16] is applied:

$$Q_N(\boldsymbol{g}_K) = \sum_{i=1}^{N} \left[ \overline{G}(t_i) - \overline{G}_K(t_i) \right]^2,$$
(5)

and the resulting task of the least-squares approximation of the spectrum H(v) by the linear combination of Hermite functions is solved. Tikhonov regularization [24] is used to guarantee the stability of the scheme for computing the vector  $\mathbf{g}_K = \begin{bmatrix} g_0 & \dots & g_{K-1} & G_\infty \end{bmatrix}^T$  of optimal model parameters. Guaranteed model approximation GMA [20,22] is adopted for the optimal choice of the best regularization parameter  $\hat{\lambda}$ . The numerical realization of the scheme by using the singular value decomposition (SVD [1]) is discussed and the resulting computer algorithm is also outlined in the previous paper [22]. The model  $\overline{G}_K(t)$  of the relaxation modulus  $\overline{G}(t)$  (2) is described by:

$$\overline{G}_{K}(t) = G_{K}(t) + G_{\infty} = \sum_{k=0}^{K-1} g_{k} \phi_{k}(t) + G_{\infty}, \quad (6)$$

where: the form of the functions  $\phi_k(t)$  are given by Theorem 1 in the paper [22]. Theoretical and simulational analysis of the identification algorithm properties and the resulting optimal model is the purpose of this paper. The proofs of the main results are omitted due to space limitations. The applications example is also given.

#### **IDENTIFICATION SCHEME**

The calculation of the relaxation spectrum model involves the following steps:

- Perform the stress relaxation test [18,19] and record the measurements G
  (t<sub>i</sub>), i=1,...,N, of the relaxation modulus at times t<sub>i</sub>≥0.
- 2. Compute the matrix  $\overline{\boldsymbol{\Phi}}_{N,K}$  [22; eq. (16)] and next examine if  $\boldsymbol{\Phi}_{N,K}^{T} \overline{\boldsymbol{G}}_{N} \neq \boldsymbol{0}_{K+1}$ , where  $\overline{\boldsymbol{G}}_{N} = [\overline{G}(t_{1}) \dots \overline{G}(t_{N})]^{T}$  is the vector of measurement data. If not, select new time-scale parameter  $\alpha$  and/or a new number K of the basis functions and repeat Step 2 or repeat the experiment (Step 1). Otherwise go to Step 3.
- 3. Determine SVD decomposition of the matrix  $\boldsymbol{\Phi}_{NK}$ :

$$\boldsymbol{\Phi}_{NK} = \boldsymbol{U} \boldsymbol{\Sigma} \boldsymbol{V}^{T}, \tag{7}$$

where:  $\Sigma = diag(\sigma_1, ..., \sigma_r, 0, ..., 0)$  is  $N \times (K+1)$  diagonal matrix containing the non-zero singular values  $\sigma_1, ..., \sigma_r$  of the matrix  $\boldsymbol{\Phi}_{N,K}$  with  $r = rank(\boldsymbol{\Phi}_{K,K})$  and  $V \in \mathbb{R}^{K+1, K+1}$  and  $U \in \mathbb{R}^{N,N}$  are orthogonal uniquely defined matrices [1].

fined matrices [1]. 4. Compute  $Q_N(\overline{g}_K^N)$  according to the formula  $Q_N(\overline{g}_K^N) = \sum_{i=r+1}^N y_i^2$ , where  $y_i$  are the elements of the vector  $\boldsymbol{Y} = \boldsymbol{U}^T \overline{\boldsymbol{G}}_N$  and  $\overline{\boldsymbol{g}}_K^N$  is the normal solution of the original (not regularized) least-squares problem (5), (6) for noise data.

5. Chose 
$$\hat{Q}_N > Q_N \left( \overline{\boldsymbol{g}}_K^N \right)$$
.

5. Chose  $Q_N > Q_N (g_K)$ . 6. Solve the GMA equation:

$$\sum_{i=1}^{r} \frac{\lambda^2 y_i^2}{\left(\sigma_i^2 + \lambda\right)^2} + Q_N\left(\overline{\boldsymbol{g}}_K^N\right) = \hat{Q}_N,\tag{8}$$

and compute the best regularization parameter  $\hat{\lambda}$ .

Compute the regularized solution:

$$\hat{\boldsymbol{g}}_{K} = \boldsymbol{g}_{K}^{\hat{\lambda}} = \boldsymbol{V}\boldsymbol{\Lambda}_{\hat{\lambda}}\boldsymbol{U}^{T}\boldsymbol{\overline{\boldsymbol{G}}}_{N}, \tag{9}$$

where: the diagonal structure matrix:

$$\Lambda_{\hat{\lambda}} = diag\left(\sigma_1 / \left(\sigma_1^2 + \hat{\lambda}\right), \dots, \sigma_r / \left(\sigma_r^2 + \hat{\lambda}\right), 0, \dots, 0\right).$$

Determine the spectrum of relaxation frequencies  $\hat{H}_{K}(v)$  according to (cf. (3)):

$$\hat{H}_{K}(\nu) = \sum_{k=0}^{K-1} \hat{g}_{k} h_{k}(\nu), \qquad (10)$$

where:  $\hat{g}_k$  are the elements of vector  $\hat{g}_k$ .

Obviously,  $\overline{H}_{K}(v) = \hat{H}_{K}(v) + G_{\infty}\delta(v)$  is the relaxation spectrum of the form [22; eq.(14)] corresponding to the optimal model of relaxation modulus of the form (6).

**Remark 1.** Only the SVD of the matrix  $\boldsymbol{\Phi}_{N,K}(7)$  is space and time consuming task of the scheme. The SVD is accessible in the form of optimized numerical procedures in most commonly used contemporary computational packets.

**Remark 2.** It is easy to note that the matrix  $\boldsymbol{\Phi}_{N,K}$  (see [22; eq. (16)]) depends on the choice of the basis functions, in particular on the scaling factor  $\alpha$  selection, as well as on the measurement points  $\{t_i\}$ , however does not depend on the experiment results. Thus, when the identification scheme is applied for successive samples of the material, the SVD of  $\boldsymbol{\Phi}_{N,K}$  in step 3 have not to be multiple repeated, while the same time instants  $\{t_i\}$  and the same model parameters  $\alpha$  and K are kept.

**Remark 3.** The Hermite functions  $h_k(v)$  defined by the formula (4) can be determined using Hermite polynomials  $P_k(x)$  [22; eqs. (3),(4)]. Polynomials  $P_k(x)$  are accessible in some computational packets; they may be also computed according to definitional recursive formula.

**Remark 4.** By the optimal choice of the scaling factor  $\alpha$ , the best fit of the model to the experimental data can be achieved. However, in practice a simple rough rule for choosing the scaling factor  $\alpha$ , based on the comparison of a few first functions from the sequence  $\{\phi_k(t)\}$  for different values of  $\alpha$  with the experimentally obtained function  $\overline{G}(t)$  is quite enough. In the same manner, the number *K* of the series (6) elements can be initially evaluated. Thus, the choice both of the number *K* as well as the parameter  $\alpha$  must be done *a posteriori*, after the preliminary experiment data analysis.

#### ANALYSIS

#### SMOOTHNESS

Since the Hermite basis functions  $h_k(v)$ , k=0,1,..., form an orthonormal basis in the Hilbert space  $L_2(-\infty,\infty)$  of real-valued square-integrable functions on the interval  $(-\infty,\infty)$  [15], for an arbitrary  $H_{\kappa}(v)$  of the form (3) the following estimation is valid:

$$\|H_{K}\|_{2}^{2} = \int_{0}^{\infty} H_{K}(v)^{2} dv \leq \\ \leq \int_{-\infty}^{\infty} H_{K}(v)^{2} dv = \sum_{k=0}^{K-1} \sum_{j=0}^{K-1} g_{k}g_{j} \int_{-\infty}^{\infty} h_{k}(v) h_{j}(v) dv,$$

and whence finally:

$$\|H_K\|_2^2 \le \sum_{k=0}^{K-1} g_k^2 = \|g_K\|_2^2.$$
(11)

Here:  $\|\cdot\|_2$  means the square norm both in the real Euclidean space as well as in  $L_2(0,\infty)$ . Therefore, the smoothness of the regularized solution  $\hat{g}_K(9)$  guarantees that the fluctuations of the respective relaxation spectrum  $\hat{H}_K(\nu)$  (10) are bounded. The Hermite algorithm is in fact quasi-orthogonal identification scheme.

#### STABILIZATION

The purpose of the regularization relies on stabilization of the resulting model vector  $g_K^{\lambda}$ . The effectiveness of this approach can be evaluated by the following relations, which follow for an arbitrary regularization parameter immediately from Proposition 2.2 in [21].

**Proposition 1.** Let  $K \ge 1$ ,  $r = rank(\boldsymbol{\Phi}_{N,K})$  and regularization parameter  $\lambda > 0$ . For the regularized solution  $\boldsymbol{g}_{K}^{\lambda}$  [22; eq. (20)] the following equality and inequality hold:

$$\left\| \boldsymbol{g}_{K}^{\lambda} \right\|_{2}^{2} = \sum_{i=1}^{r} \frac{\sigma_{i}^{2} y_{i}^{2}}{\left(\sigma_{i}^{2} + \lambda\right)^{2}} < \sum_{i=1}^{r} \frac{y_{i}^{2}}{\sigma_{i}^{2}} = \left\| \overline{\boldsymbol{g}}_{K}^{N} \right\|_{2}^{2}, \quad (12)$$

where:  $\overline{g}_{K}^{N}$  is the normal solution of the linear-quadratic problem (5),(6).

Therefore, by (12) the following rule holds: the greater the regularization parameter  $\lambda$  is, the fluctuations of the vector  $\mathbf{g}_{K}^{\lambda}$  are highly bounded. Thus, the regularization parameter controls the smoothness of the regularized solution. Simultaneously, however, the best – in the GMA sense – parameter  $\hat{\lambda}$  is monotonically increasing function of  $\hat{Q}_{N}$ . Thus, it is immediately evident that, the worse the relaxation modulus measurements approximation quality is, the regularized vector  $\hat{\mathbf{g}}_{K}$  and, in view of (11), the computed spectrum  $\hat{H}_{K}(\nu)$  are highly smoothed. The upper bounds of the vector  $\hat{\mathbf{g}}_{K}$  and the norm of spectrum  $\hat{H}_{K}(\nu)$  are established by our next result.

**Proposition 2.** Let  $K \ge 1$ ,  $N \ge K$  and  $\hat{Q}_N > Q_N(\overline{g}_K^N)$ . Then, for the GMA regularized solution  $\hat{g}_K$  (9) the following estimations hold:

$$\left\|\hat{H}_{K}\right\|_{2}^{2} \leq \left\|\hat{\boldsymbol{g}}_{K}\right\|_{2}^{2} \leq \left(\sum_{i=1}^{r} \sigma_{i}^{2} y_{i}^{2}\right) \left(\sum_{i=1}^{r} y_{i}^{2} / \sigma_{i}^{4}\right) / \left(\hat{Q}_{N} - \sum_{i=r+1}^{N} y_{i}^{2}\right).$$
(13)

#### CONVERGENCE

Let us estimate the regularized vector  $\hat{\boldsymbol{g}}_{K}$  error, which is measured by the norm  $\|\hat{\boldsymbol{g}}_{K} - \boldsymbol{g}_{K}^{N}\|_{2}^{2}$ , where  $\boldsymbol{g}_{K}^{N}$  is the normal solution of the least-squares task (5),(6) for noise-free data. Obviously, relaxation spectrum  $\hat{H}_{K}(v)$  (10) is only approximation of that spectrum, which can be obtained in the class of models (3) by direct minimization (without regularization) of the quadratic index (5) for noise-free measurements, i.e. the approximation of the function  $H_{K}^{N}(v) = \sum_{k=0}^{K-1} g_{k}^{N} h_{k}(v)$ , where  $\boldsymbol{g}_{K}^{N}$  are the elements of vector  $\boldsymbol{g}_{K}^{N}$ . We have the following convergence result.

**Proposition 3.** Let  $K \ge 1$ ,  $N \ge K$  and  $\hat{Q}_N > Q_N(\overline{g}_K^N)$ . Then, the following inequalities hold:

$$\left\|\hat{H}_{K}-H_{K}^{N}\right\|_{2} \leq \left\|\hat{\boldsymbol{g}}_{K}-\boldsymbol{g}_{K}^{N}\right\|_{2} \leq \frac{1}{\sigma_{r}}\sqrt{\hat{\mathcal{Q}}_{N}-\mathcal{Q}_{N}\left(\overline{\boldsymbol{g}}_{K}^{N}\right)}+\frac{1}{\sigma_{r}}\left\|\boldsymbol{z}_{N}\right\|_{2}, \quad (14)$$

where:  $\mathbf{z}_N = [z(t_1) \dots z(t_N)]^T$  is the measurement noises vector.

Therefore, the vector  $\hat{\mathbf{g}}_{K}$  converges to the normal solution  $\mathbf{g}_{K}^{N}$ , and the spectrum  $\hat{H}_{K}(\nu)$  tends to the 'normal' spectrum  $H_{K}^{N}(\nu)$  in each point  $\nu$ , at which they are both continuous, linearly with respect to the norm  $||\mathbf{z}N||_{2}$ , as  $\hat{Q}_{N} \rightarrow Q_{N}(\overline{\mathbf{g}}_{K}^{N})$  and  $||\mathbf{z}N||_{2} \rightarrow 0$ , simultaneously.

Thus, the accuracy of the spectrum approximation depend both on the measurement noises and the assumed model quality as well as on the singular values of the matrix  $\boldsymbol{\Phi}_{N,K}$ , which, in turn, depend on the proper selection of the time-stale factor  $\alpha$  of  $h_k(v)$  (see Remark 4).

#### SIMULATION STUDIES OF NOISE ROBUSTNESS

We now present the results of the theoretical and numerical studies of the influence of the measurement noises on regularized solution. The experiment simulations are conducted using Gaussian relaxation spectrum. Such an example illustrates most of the works concerning relaxation or retardation spectrum identification, for example [4,23].

**Example 1.** Consider viscoelastic material whose relaxation spectrum is described by the Gauss distribution:

$$H(\nu) = \frac{1}{6\sqrt{2\pi}} e^{-(\nu-20)^2/72}.$$
 (15)

The corresponding relaxation modulus is described by:

$$G(t) = \frac{1}{2}e^{-20t+18t^2} erfc \left(3\sqrt{2}t - 5\sqrt{2}/3\right), \qquad (16)$$

where: erfc(t) is defined by [22; eq. (11)].

The spectrum H(v) (15) is given in Figure 3 (dashed line). In experiment the sampling instants

 $t_i$  was generated in the constant period in time interval T = [0;0,4] seconds selected on the basis of the relaxation modulus G(t) (16) course in time. In order to study the influence of the noise variance  $\sigma^2$  on the vector of model parameters measurement noises  $\{z_i\}$ have been generated randomly with uniform distribution on the interval [-h,h] for h=0,0005;0,001;0,005;0,01and N=100,500,1000,5000,10000. h=0,01 is 1% of the maximum value of G(t) and h=0,0005 is about 1% of the mean value of the modulus. Such measurement noises are even strongest than the true disturbances recorded for the biological materials (see [21, Chapter 5.5.4]). In the case of the sugar beet sample from example 3 below disturbances have not exceeded 0,8% of the maximum value of G(t) and have not exceeded 0,7% of the mean value of the modulus. The experiment have been repeated n=500 times for every pair  $(N,\sigma^2)$  for K=6 and K=8.

The distance between  $\hat{g}_{K}$  and the regularized parameter for noise-free measurements:

$$\tilde{\boldsymbol{g}}_{K} = \boldsymbol{g}_{K}^{\tilde{\lambda}} = \boldsymbol{V}\boldsymbol{\Lambda}_{\tilde{\lambda}}\boldsymbol{U}^{T}\boldsymbol{G}_{N}, \qquad (17)$$

has been estimated by normalized mean error defined for *n* element sample as:

$$ERR\left(N,K,\sigma^{2}\right) = \frac{1}{n} \sum_{j=1}^{n} \left\| \hat{\boldsymbol{g}}_{K,j} - \tilde{\boldsymbol{g}}_{K,j} \right\|_{2} / \left\| \tilde{\boldsymbol{g}}_{K,j} \right\|_{2}, \quad (18)$$

where:  $\hat{\boldsymbol{g}}_{K,j}$  denote the regularized model parameter  $\hat{\boldsymbol{g}}_{K}$  for noise case and  $\tilde{\boldsymbol{g}}_{K,j}$  is the regularized noise-free parameter determined for *j*-*th* experiment repetition for



The ranges of variation of the index  $ERR(N,K,\sigma^2)$ obtained in the simulation experiment are given in table 1. Time-scale factor  $\alpha = 0.06[s]$  was taken and kept valid in all the simulation experiments. Since the index  $Q_N(\overline{\boldsymbol{g}}_K^N)/N$ was included in the range from 3,0722E-6 (for small noises) to 2,578E-4 (for strong noises), the assumed value of model approximation index  $Q_N$  was taken such that  $Q_N$ /N vary in the range from 0,050 to 0,087, respectively, for small and strong noises. The index  $ERR(N,K,\sigma^2)$  depends on the noise variance as well as on the matrix  $\boldsymbol{\Phi}_{_{NK}}$  and on the assumed value of model approximation index  $Q_N$ . The index  $ERR(N,K,\sigma^2)$  does not depend essentially on the number of measurements but significantly depends on the intensity of noises. The algorithm ensures very good noise robustness for small and medium disturbances; the index  $ERR(N,K,\sigma^2)$  does not exceed 1,5%. For large noises the index  $ERR(N,K,\sigma^2)$  do not exceed 8%. The next two examples show how the scheme proposed can be used in the relaxation spectrum identification.

**Table 1.** The ranges of variation of the error index  $ERR(N,K,\sigma^2)$  obtained in the simulation experiment

$ERR(N,K,\sigma^2)$	h=0,0005	h=0,001	<i>h</i> =0,005	h=0,01
<i>K</i> =6	0,0022÷0,0049	0,0044÷0,0096	0,0219÷0,036	0,0402÷0,0791
K=8	0,006÷0,0095	0,0097÷0,0157	0,0465÷0,0643	0,0537÷0,077



**Fig. 1.** The index  $ERR(N,K,\sigma^2)$  as a function of N and  $\sigma^2$  for K=6



**Fig. 2.** The index  $ERR(N,K,\sigma^2)$  as a function of N and  $\sigma^2$  for K=6



Fig. 3. Relaxation spectrum H(v) (15) (dash line) and the approximated model  $\hat{H}_{K}(v)$  (solid line).

**Example 2.** Let us consider again the Gaussian spectrum H(v) (15). The modulus  $\overline{G}(t) = G(t) + z(t)$  corrupted by noises z(t) of the uniform distribution in the interval [-0,02; 0,2] has been sampled at N=500 instants at the constant period  $\Delta t = 0,0008[s]$ . The parameters K=8 and  $\alpha = 0,06[s]$  are chosen according to Remark 4.

Since  $Q_N(\overline{g}_K^N) = 0,06495$ , the assumed value of model quality is taken as follows:  $\hat{Q}_N = 0,06527$ . The GMA regularization parameter:  $\hat{\lambda} = 5E - 5$ . The true relaxation spectrum H(v) (15) and the resulting approximated model  $\hat{H}_K(v)$  (10) are plotted in Figure 3.

#### RELAXATION SPECTRUM OF THE SUGAR BEET SAMPLE

Example 3. A cylindrical sample of 20 [mm] diameter and height was obtained from the root of sugar beet Janus variety [9]. During the stress relaxation test performed by Gołacki and co-workers [9], in the initial phase the strain was imposed instantaneously, the sample was preconditioned at the  $0.5 [m \cdot s^{-1}]$  strain rate to the maximum strain. Next, during the second phase at constant strain the corresponding time-varying force induced in the specimen was recorded during the time period [0,5;96,2] seconds in 958 measurement points with the constant sampling period  $\Delta t = 0,1[s]$ . The experiment was performed in the state of uniaxial stress; i.e. the specimen examined underwent deformation between two parallel plates (for details see [9]). Modelling mechanical properties of this material in viscoelastic regime is justified in view of many studies, e.g., [2,9]. The respective relaxation modulus were computed using simple modification of the well-known Zapas and Craft rule [19] derived in [21].



**Fig. 4.** The relaxation spectrum models  $\hat{H}_{K}(\nu)$  of two samples of beet sugar root



**Fig. 5.** The relaxation modulus measurements  $\overline{G}(t_i)$  (points) and the best model  $\overline{G}_k(t)$  (solid line) for two samples

The proposed identification scheme was applied and the relaxation spectra obtained are plotted in Figure 4 for two samples. The respective optimal models  $\overline{G}_K(t) = \sum_{k=0}^{K-1} \hat{g}_k \phi_k(t) + \hat{G}_{\infty}$  are plotted in Figure 5, where the relaxation modulus measurements are also shown. For both samples K=8 and  $\alpha = 10,4[s]$  was chosen. The computed long-term modulus was as follows:  $\hat{G}_{\infty} = 3,436 [MPa]$  and  $\hat{G}_{\infty} = 6,877 [MPa]$ .

#### CONCLUSIONS

An algorithm has been found for the calculation of relaxation spectrum from the discrete-time measurement data of the linear relaxation modulus. Tikhonov regularization and guaranteed model approximation are used to solve it. As a result, the stability of the scheme is guaranteed. Due to the choice of the Hermite basis functions, for which the basis functions for relaxation modulus are given by the convenient recursive formula, the algorithm is very useful for implementation. This choice also guarantees that smoothing of the regularized solution ensures smoothing of the relaxation spectrum model. The choice of the scaling-time factor in order to achieve a good fit of the model to the experimental data is discussed and the noise robustness is demonstrated. It is also indicated that the accuracy of the spectrum approximation depends both on measurement noises and regularization parameter and on the proper selection of the time-scale parameter of the basis functions.

Although the paper is concerned with the relaxation spectrum identification using stress experiment data, a modification of the scheme proposed for determination of the retardation spectrum using the creep compliance measurements obtained in creep test [18] is possible as well.

The proposed method \ provides us with the tool for relaxation spectrum identification applicable for an arbitrary viscoelastic material. We consider a situation where only the time-measurements from relaxation test are accessible for identification. This is important in studying the rheological properties of many materials, e.g., biodegradable materials [6], different pelets [3], livestock meat [17] and different plant materials [2, 9, 18]. The proposed method leads to insights into how to estimate the laws of such materials. Therefore it lies in the broad area of studying mechanical properties of such materials [7, 8, 10, 13,14].

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#### ALGORYTM IDENTYFIKACJI SPEKTRUM RELAKSACJI MATERIAŁÓW LEPKOSPRĘŻYSTYCH NA PODSTAWIE ZAKŁÓCONYCH POMIARÓW MODUŁU RELAKSACJI

Streszczenie. W pracy przedstawiono algorytm identyfikacji ciągłego spektrum relaksacji materiałów liniowolepkosprężystych na podstawie dyskretnych zakłóconych pomiarów z testu relaksacji naprężeń. Model spektrum relaksacji dany jest kombinacją liniową funkcji Hermita. Jego parametry dobrano optymalnie w sensie zregularyzowanej metody najmniejszej sumy kwadratów. Zastosowano regularyzację Tichonowa, współczynnik regularyzacji dobrano metoda gwarantowanej jakości modelu. Zbadano własności algorytmu i wyznaczonego modelu. Dla pomiarów z nałożonym szumem wykazano jego liniową zbieżność. Pokazano, że dokładność przybliżenia spectrum relaksacji zależy zarówno od intensywności zakłóceń oraz współczynnika regularyzacji jak i odpowiedniego doboru parametrów funkcji bazowych modelu. Przeprowadzone badania symulacyjne potwierdziły dokładność modelu i jego odporność na zakłócenia. Wyznaczono spektrum relaksacji dwu przykładowych próbek buraka cukrowego.

Słowa kluczowe: spektrum relaksacji, algorytm identyfikacji, regularyzacja, funkcje Hermita

# Design scheme for the stress relaxation experiment for maxwell model identification

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Summary. The problem of a weighted least-squares approximation of viscoelastic material by Maxwell model is discussed when the noise-corrupted time-measurements of the relaxation modulus obtained in relaxation test experiment are accessible for identification. In the previous paper it has been shown that even when the true relaxation modulus description is completely unknown, the optimal Maxwell model parameters can be derived from the measurement data sampled randomly according to appropriate randomization. In this paper an identification algorithm leading to the best model when only a relaxation modulus data are accessible is derived using a concept of random choice of the sampling instants. The stochastic-type convergence analysis is conducted both for corrupted as well as noise free relaxation modulus measurements and the exponential convergence rate is proved. Experimental numerical results for five-parameter Maxwell model are provided. Applying the scheme proposed the four-parameter Maxwell models of an confined cylindrical specimen of the beet sugar root are determined for a few sets of relaxation modulus measurement data and the convergence of the sequence of best model parameters is demonstrated. The procedure has been successfully tested using both artificial and experimental data.

Key words: relaxation test, Maxwell model, identification algorithm, experiment design

#### **INTRODUCTION**

The classical Maxwell model [14] is a viscoelastic body that stores energy like a linearized elastic spring and dissipates energy like a classical fluid dashpot. The generalized Maxwell model, which is used to describe the relaxation modulus of linear viscoelastic materials, consists of a spring and n Maxwell units connected in parallel. Maxwell models are used frequently to describe viscoelasticity of polymers [1, 6], concrete [13], soils [5], rocks [8], rubber [20], glass [17], foods [16] and biological materials [2, 9].

Maxwell models described by a sum of exponential functions. Fitting a sums of exponentials to empirical data

is a very old problem in system identification theory [7, 10]. Although a lot of methods are known for determining exponential sum models, in particular for finding the optimal least-squares exponential sum approximations to sampled data, the efficient tools for Maxwell model determination are still desirable and this is the purpose of this study.

In empirical sciences there is an increasing use of mathematical models to describe various physical phenomena. The work in modelling of physical phenomena neatly partitions into two pieces: the work in acquiring information (measurements) from the real system, and the overhead involved in determining the best model. More often than not, this second part of the work is dominated by system identification methods. Whence, members of the physical systems researchers community have been consumers of system identification algorithms. Thus, their needs have set some research directions for the system identification community. Simultaneously, this symbiotic relationship has entered a new phase, in which the new advances in system identification contribute to building a better and better models and they are also setting new research agendas for the physical systems researchers community.

In the previous paper [19] an idea of measurement point-independent approximation of a relaxation modulus of linear viscoelastic materials within the class of generalized Maxwell models, when the integral weighted square error is to be minimized and the true material description is completely unknown, is presented. In this paper a simple identification algorithm providing the strongly consistent estimate of the optimal model is given. Next, the rate of convergence is discussed for the case when the measurements are perfect or corrupted by additive noises. The results of simulation experiments for five parameter Maxwell model are presented and the identification algorithm is applied for computing the Maxwell model of an specimen of the beet sugar root.

#### OPTIMAL IDENTIFICATION OF MAXWELL MODEL

In the previous paper [19] the problem of an approximation of relaxation modulus G(t) of linear viscoelastic material by generalized Maxwell model:

$$G_{M}(t,\boldsymbol{g}) = \sum_{j=1}^{n} E_{j} e^{-v_{j}t} + E_{\infty}, \qquad (1)$$

with the vector of model parameters defined as:

$$\boldsymbol{g} = \begin{bmatrix} E_1 & \dots & E_n & v_1 & \dots & v_n & E_{\infty} \end{bmatrix}^T, \qquad (2)$$

where:  $E_j$ ,  $v_j$  and  $E_{\infty}$  are the elastic modulus, relaxation frequencies and equilibrium modulus, respectively, is considered under the assumption that the exact mathematical description of the true relaxation modulus G(t) is completely unknown. The value of G(t) can be, however, measured with a certain accuracy for any given value of the time  $t \in T$ , where T=[0,T] and  $0 < T < \infty$  or  $T=R_+$ ; here  $R_+=[0,\infty)$ . The restriction that the model parameters are nonnegative and confined must be given to satisfy the physical meaning, i.e.  $g \in G$ , where the admissible set of parameters G is compact subset of the space  $R_+^{2n+1}$ .

Let  $T_1,...,T_N$  are independent random variables with a common probability density function  $\rho(t)$  whose support is  $\mathcal{T}$ . Let  $\overline{G}_i = G(T_i) + Z_i$  denote measurements of the relaxation modulus  $G = G(T_i)$  obtained in a certain stress relaxation test performed on the specimen of the material under investigation, i=1,...,N. Here  $Z_i$  are additive measurement noises.

As a measure of the model (1) accuracy the global approximation error of the form:

$$Q(\mathbf{g}) = \int_{\mathcal{T}} \left[ G(t) - G_M(t, \mathbf{g}) \right]^2 \rho(t) dt, \qquad (3)$$

where a chosen weighting function  $\rho(t) \ge 0$  is a density on *T*, i.e.,  $\int_{T} \rho(t) dt = 1$ , is applied. From practical reasons the global index Q(g) is replaced by the following empirical one:

$$Q_N(\boldsymbol{g}) = \frac{1}{N} \sum_{i=1}^{N} \left[ \overline{G}_i - G_M(T_i, \boldsymbol{g}) \right]^2.$$
(4)

Therefore, the classical least-squares problem for Maxwell model is obtained.

The problem of the relaxation modulus G(t) optimal approximation within the class of Maxwell models (1) consists in determining the admissible parameter minimizing Q(g):

$$\boldsymbol{g}^* = \arg\min_{\boldsymbol{g}\in \mathcal{G}} \mathcal{Q}(\boldsymbol{g}), \tag{5}$$

Here arg min  $g \in G Q(g)$  denotes the vector g that minimizes Q(g) on the set G. The respective empirical task is as follows:

$$\boldsymbol{g}_{N} = \arg \min_{\boldsymbol{g} \in \mathcal{G}} \mathcal{Q}_{N}\left(\boldsymbol{g}\right). \tag{6}$$

Under standard assumptions concerning the relaxation modulus and noises:

- Assumption 1. The relaxation modulus G(t) is bounded on  $\mathcal{T}$ , i.e.  $sup_{t=T}G(t) \leq M \leq \infty$ ,
- Assumption 2. The measurement noises  $Z_i$  are bounded, i.e.  $|Z_i| \le \delta \le \infty$  for i = 1, ..., N,
- Assumption 3.  $\{Z_i\}$  is a time-independent sequence of independent identically distributed (i.i.d.) random variables with zero mean and a common finite variance  $\sigma^2$ ,

it is shown in [19], that Maxwell model which is asymptotically (when the number of measurements tends to infinity) independent on the particular sampling instants  $t_i$  can be derived from the set of relaxation modulus timedata by introducing a simple randomization. Namely, it is proved that if the Assumptions 1-3 hold and  $T_1,...,T_N$  are independently, at random selected from T, each according to probability distributions with density  $\rho(t)$ , then both for perfect as well as for the additive noise corrupted relaxation modulus measurements:

$$\boldsymbol{g}_N \to \boldsymbol{g}^* \qquad w.p.1 \quad as \quad N \to \infty$$
 (7)

and for all  $t \in T$ :

$$G_M(t, \boldsymbol{g}_N) \to G_M(t, \boldsymbol{g}^*) \quad w.p.1 \quad as \quad N \to \infty,$$
 (8)

where *w.p.*1 means "with probability one". Thus, the model parameter  $g_N$  is strongly consistent estimate of the parameter  $g^*$ . Moreover, since the model  $G_M(t,g)$ is Lipschitz on G uniformly in  $t \in T$ , then the almost sure convergence of  $g_N$  to  $g^*$  in (7) implies that:

$$\sup_{t\in\mathcal{T}} \left| G_M\left(t, \boldsymbol{g}_N\right) - G_M\left(t, \boldsymbol{g}^*\right) \right| \to 0 \qquad \text{w.p.1} \quad as \quad N \to \infty.$$
(9)

Thus,  $G_M(t, \boldsymbol{g}_N)$  is a strongly uniformly consistent estimate of the best model  $G_M(t, \boldsymbol{g})$ .

Summarizing, when the Assumptions 1-3 are satisfied, the arbitrarily precise approximation of the optimal Maxwell model (with the parameter  $g^*$ ) can be obtained (almost everywhere) as the number of mesurements Ngrows large, despite the fact that the real description of the relaxation modulus is completely unknown.

#### IDENTIFICATION ALGORITHM

Taking into account the convergence results (7)-(9) the calculation of the approximate value  $g_N$  of optimal Maxwell model parameter  $g^*$  involves the following steps. 1. Select randomly from the set T the sampling instants

- $t_1, \dots, t_N$ , each  $t_i$  independently, according to the probability distribution on T with the density given by the weighting function  $\rho(t)$  in (3).
- 2. Perform the stress relaxation test, record and store the relaxation modulus measurements  $\overline{G}(t_i)$ , i=1,...,N, corresponding to the chosen points  $t_i \ge 0$ .
- 3. Solve the optimization task (6) and compute the Maxwell model parameter  $g_{N}$ .

4. In order to ascertain if  $g_N$  is a satisfactory approximation of  $g^*$  enlarge the set of data to the extent  $\overline{N} >> N$  we

repeating Steps 1 and 2.

- 5. Execute Step 3 for the new set of data determining  $g_{\overline{N}}$ .
- 6. Examine if  $\|\boldsymbol{g}_N \boldsymbol{g}_{\overline{N}}\|_2 < \varepsilon$ , for  $\varepsilon$ , a small positive number. If not, put  $N = \overline{N}$  and go to Step 4. Otherwise, stop the procedure taking  $\boldsymbol{g}_N$  as the approximate value of  $\boldsymbol{g}^*$ .

**Remark.** The stopping rule from Step 6 can be replaced by a less restrictive one, based on testing, whether  $|Q_{\overline{N}}(\boldsymbol{g}_{\overline{N}}) - Q_{N}(\boldsymbol{g}_{N})| < \varepsilon$  holds. Both the stopping rules considered correspond with those commonly used in the numerical minimization techniques.

#### CONVERGENCE ANALYSIS

Taking account of (7) the question immediately arises how fast does  $\boldsymbol{g}_N$  tend to  $\boldsymbol{g}^*$  as N grows large. The distance between the Maxwell model parameters  $\boldsymbol{g}_N$  and  $\boldsymbol{g}^*$  will be estimated in the sense of quality difference  $|Q(\boldsymbol{g}^*) - Q(\boldsymbol{g}_N)|$ . We shall examine how fast, for given  $\varepsilon > 0$ , does  $P\{|Q(\boldsymbol{g}^*) - Q(\boldsymbol{g}_N)| \ge \varepsilon\}$  tend to zero as N increases. On the basis of inequality (11) from [4] we obtain for noise case the following bound:

$$P\left\{ \left| Q_{N}\left( \mathbf{g} \right) - Q\left( \mathbf{g}^{*} \right) \right| \ge \varepsilon \right\} \le 2 \exp\left( -N\varepsilon^{2} / 8\hat{M}^{2} \right), \tag{10}$$

where  $\hat{M}$  is such that the next estimation is valid for any  $g \in G$ :

$$\left[ G(T_i) + Z_i - G_M(T_i, \mathbf{g}) \right]^2 - \left[ \mathcal{Q}(\mathbf{g}) + \sigma^2 \right] \\ \leq \tilde{M} + \delta^2 + 2c\delta + \sigma^2 = \hat{M}. \quad (11)$$

Here a positive constant  $\tilde{M}$  is such that:

$$\left[G(T_i) - G_M(T_i, \mathbf{g})\right]^2 - Q(\mathbf{g}) \le \tilde{M}$$
(12)

for any  $g \in G$ , i=1,...,N, and a positive constant c is defined by the inequality  $|G(T_i)-G_M(T_i,g)| \le c$  which holds for every  $g \in G$ , i=1,...,N. The existence of  $\tilde{M}$  follows immediately from the Assumptions 1 and 2, Property 3 and the fact that, the weighting function  $\rho(t) \ge 0$  is a density on T. In view of Assumption 1 and Property 2 the positive constant c there exists and can be evaluated without a difficulty. Note also, that in the noiseless case the inequality (10) takes especially simple form:

$$P\left\{ \left| Q_{N}\left( \mathbf{g}\right) - Q\left( \mathbf{g}^{*} \right) \right| \ge \varepsilon \right\} \le 2 \exp\left( -N\varepsilon^{2} / 8\tilde{M}^{2} \right).$$
(13)

The inequalities (13) and (10) show some connections between the convergence rate and the number of measurements N as well as the measurement noises. In particular, if  $\varepsilon$  is fixed, then the bound (10) tends to zero at exponential rate as N increases. Note also, that the rate of convergence is the higher the lower is  $\hat{M}$ , thus by (11) the lower are  $\delta$  and  $\sigma^2$ , i.e. the measurement noises are weaker. This is not a surprise since, with large noises, the measurements are not much adequate to the true relaxation modulus. Notice, however, that for fixed  $\varepsilon > 0$ both for noiseless as noise case:

$$P\left\{ \left| Q_{N}(\mathbf{g}) - Q(\mathbf{g}^{*}) \right| \ge \varepsilon / N^{\alpha} \right\} \le 2 \exp\left( -N^{(1-2\alpha)} \varepsilon^{2} / 8\hat{M}^{2} \right)$$

with  $0 \le \alpha \le 1/2$  still tends to zero as  $N \rightarrow \infty$  in quasi-exponential rate.

We now present the results of the numerical experiments. Both the asymptotic properties (as the number of measurements  $N \rightarrow \infty$ ) as well as the influence of the measurement noises on solution will be studied.

#### EXPERIMENTAL STUDIES

Consider viscoelastic material whose relaxation modulus is described by:

$$G(t) = \frac{1}{2}e^{-20t+18t^2} erfc \left(3\sqrt{2}t - 5\sqrt{2}/3\right) + 0.2,$$
(14)

where erfc(t) is the complementary error function [11]. The time interval T=[0;0,8] seconds has been taken for the experiment in view of the modulus G(t) (14) course. The measurement points  $t_i$  are selected randomly, each  $t_i$ independently according to the uniform distribution on T. The 5 parameter Maxwell model of the form:

$$G_M(t) = E_1 e^{-\nu_1 t} + E_2 e^{-\nu_2 t} + E_{\infty},$$

has been taken for numerical studies. The relaxation modulus  $\overline{G}(t_i) = G(t_i) + z(t_i)$  has been sampled in N sampling instants during the time period T.

In order to study the influence of the noises on the Maxwell model parameters  $\{z_i\}$  have been generated independently by random choice with normal distribution with zero mean value and variance  $\sigma^2$ ;  $\sigma$ =0.005,0.0075,0.01,0.02 is taken for experiment. Such measurement noises are even strongest than the true disturbances recorded for the plant materials (see [18; Chapter 5.5.4]). For the analysis of asymptotic properties of the scheme N=50,100,500,1000,5000,10000 has been used in the experiment. The experiment and next the computation of the optimal model have been repeated n=100 times for every pair (N,  $\sigma^2$ ). The distance between the optimal model parameters: 'empirical'  $g_N$  and 'ideal'  $g^*$  has been estimated by standardized mean error defined for n element sample as:

$$ERR(N,\sigma^{2}) = \frac{1}{n} \sum_{j=1}^{n} \left\| \mathbf{g}_{N,j} - \mathbf{g}^{*} \right\|_{2} / \left\| \mathbf{g}^{*} \right\|_{2}, \quad (15)$$

where  $g_{N,j}$  denote the model parameter  $g_N$  determined for j-th experiment repetition for a given pair  $(N, \sigma^2)$ , j=1,...,n. Here  $\|\cdot\|_2$  denotes the Euclidean norm in the space  $R^{2n+1}$ . Relationship of  $ERR(N, \sigma^2)$  (15) on N and  $\sigma^2$ is depicted in Figure 1. The ranges of variation of the index  $ERR(N, \sigma^2)$  obtained in the simulation experiment are given in table 1. In Figure 1 we can see that for small and middle noises and  $N \ge 500$  the error  $ERR(N, \sigma^2)$  does not depend essentially on the number of measurements. For small and middle noises the index  $ERR(N, \sigma^2)$  do not exceed 2%, however, for large noises ( $\sigma = 0.02$ ) this error exceeds 10%.



**Fig. 1.** The index *ERR*(*N*,  $\sigma^2$ ) as a function of *N* and  $\sigma^2$ 



**Fig. 2.** The mean square approximation error of the relaxation modulus measurements  $ERRQ_N(N, \sigma^2)$ ; the notation [4·10<sup>-4</sup>]\*0.3 is used to describe the function  $0.3 \cdot ERRQ_N(N, \sigma^2)$  for  $\sigma^2 = 4 \cdot 10^{-4}$ .

To estimate the approximation error of the relaxation modulus measurements for n-element sample the following index (cf. definition (4)) is taken:

$$ERRQ_{N}\left(N,\sigma^{2}\right) = \frac{1}{nN}\sum_{j=1}^{n}Q_{N}\left(g_{N,j}\right) =$$
$$= \frac{1}{nN}\sum_{j=1}^{n}\sum_{i=1}^{N}\left[\overline{G}_{i,j} - G_{M}\left(t_{i,j},g_{N,j}\right)\right]^{2},$$

where  $\overline{G}_{i,j} = G(t_{i,j}) + z_{i,j}$  denote the relaxation modulus measurements for j-th experiment repetition for a given pair  $(N, \sigma^2), j=1,...,n$ . The index  $ERRQ_N(N, \sigma^2)$ as a function of N and  $\sigma^2$  is depicted in Figure 2. We can see that  $ERRQ_N(N, \sigma^2)$  does not depend essentially on the number of measurements both for small as well as large noises. The algorithm ensures very good quality of the measurements approximation even for large noises (see table 1).

The mean integral error of the relaxation modulus G(t) (14) approximation is defined as:

$$ERRQ(N,\sigma^2) = \frac{1}{n} \sum_{j=1}^{n} Q(\boldsymbol{g}_{N,j}),$$

where the global integral error is given by (3). The error  $ERRQ(N, \sigma^2)$  is decreasing function of the number of sampling points and the number of model summands as depicted in Figure 3. The interpretation of Figure 3 becomes quite clear when we take into account the convergence analysis conducted. As we have shown, the global integrated index Q(g) converges exponentially both with the increase of the number of measurements N as well as with the decrease of the noise variance  $\sigma^2$  – compare the inequality (10) and the definition of  $\hat{M}(10)$ .



**Fig. 3.** Mean integral approximation error of the relaxation modulus  $ERRQ(N, \sigma^2)$ 

**Table 1.** The ranges of variation of the approximation error indices used in the simulation experiment for the number of measurements  $N \ge 500$ 

	σ=0,005	σ=0,0075	$\sigma = 0,01$	$\sigma = 0,02$
$ERR(N, \sigma^2)$	0,00408÷0,0128	0,0087÷0,01757	0,0182÷0,0213	0,12175÷0,1284
$ERRQ_{N}(N, \sigma^{2})$	2,47E-5÷2,51E-5	5,56E-5÷5,63E-5	9,88E-5÷9,9E-5	1,17E-4÷1,18E-4
$ERRQ(N, \sigma^2)$	0,0189÷0,0193	9,98E-3÷0,018	9,167E-3÷0,017	1,2E-3÷4,518E-3

**Table 2.** Maxwell model (16) parameters and the values of identification index  $Q_N(\boldsymbol{g}_N)$ ; random choice of the sampling instants

	$N \qquad Q_N(\boldsymbol{g}_N)$	Model parameters			
Ν		$\begin{bmatrix} E_{1,N} \\ [MPa] \end{bmatrix}$	$E_{2,N}$ [ <i>MPa</i> ]	$v_{1,N}[s^{-1}]$	$v_{2,N} \ [s^{-1}]$
15	7,914E-5	10,2607	0,5257	4,6823E-4	0,0489
20	2,978E-4	10,3447	0,5097	5,4625E-4	0,0737
25	8,38E-4	10,4025	0,5292	6,3646E-4	0,1004
40	2,233E-3	10,3763	0,5886	5,8039E-4	0,0963
50	1,867E-3	10,3553	0,6049	5,5898E-4	0,0886
75	4,575E-4	10,3388	0,5736	5,3957E-4	0,0793
100	2,527E-4	10,2973	0,5409	4,9971E-4	0,0598
150	2,596E-4	10,2879	0,5363	4,8541E-4	0,0582
200	2,912E-4	10,2936	0,5342	4,9343E-4	0,0587
250	3,476E-4	10,2877	0,5427	4,7722E-4	0,0584
300	2,541E-4	10,284	0,5398	4,8225E-4	0,0561
350	2,615E-4	10,2785	0,5369	4,7334E-4	0,0557
400	2,851E-4	10,2786	0,5383	4,7207E-4	0,0564

The next example shows how the proposed identification scheme can be used in the Maxwell model identification of real material.

## MAXWELL MODEL OF THE SUGAR BEET SAMPLE

Let us consider again the sample of the root of sugar beet Janus variety [3] studied in the example in [19]. The stress relaxation experiment performed by Gołacki and co-workers is described in details in [3] and the way how the experiment data has been preliminary proceeded is circumscribed in paper [19]. The sampling points  $t_i$ have been generated independently by random choice with uniform distribution in time interval [0;95] seconds, consecutively, for N from the set N1 = {15,20,25,40,50, 75,100,150,200,250,300,350,400}, and the respective relaxation modulus measurements have been selected from the whole set of measurement data. Next, the optimal four-parameter Maxwell models:

$$G_M(t) = E_1 e^{-\nu_1 t} + E_2 e^{-\nu_2 t}, \tag{16}$$

were determined for each *N*. The parameters of the optimal models and the respective values of empirical index  $Q_N(\mathbf{g})$  (4) are given in Table 2. The fast convergence of the model parameters and the model quality index is illustrated in Figures 4 and 5, respectively. In Figure 6 the distance  $d_N = ||\mathbf{g}_N - \mathbf{g}_{[N]}||_2$ , between the successive model parameters  $\mathbf{g}_N$  is also shown as a function of *N*, where [N] is a direct predecessor of *N* in the set N.



Fig. 4. The optimal Maxwell model parameters as a function of the number of measurements *N*; random choice of the sampling instants



Fig. 5. The identification index  $Q_N(g_N)$  as a function of the number of measurements N; random choice of the sampling instants



**Fig. 6.** The distance  $d_N$  between the two successive Maxwell model parameters  $g_N$  as a function of the number of measurements N; random choice of the sampling instants

The fitting of the relaxation modulus computed according to the best Maxwell models  $G_M(t, \mathbf{g}_N)$  to experiment data is shown for a few values of the number of measurements in Figure 7, where the measurements  $\overline{G}(t_i)$ are also marked. It can be seen from Figure 7 that four parameter Maxwell models are necessary for almost excellent fitting the data, if the time instants  $t_i$  are chosen in appropriate way.

The differences in the convergence speed between the cases of random and equidistant experiment data are demonstrated by comparison of Figures 5,6 and 2 in [19], Figures 7 and 3 in [19]. Thus, the general conclusion is that the choice of the sampling instants has fundamental meaning for the Maxwell model obtained.

#### FINAL REMARKS

- 1. The approximation of the optimal Maxwell model can be derived from relaxation modulus data sampled randomly according to respective randomization. The approximate model parameters are strongly consistent estimate of the parameters of that Maxwell model, which is independent of particular sampling instants used in relaxation test.
- 2. It is worth of noticing that the resulting identification procedure is very useful in application because it does not require any other experimental technique more sophisticated than the independent random sampling of time instants  $t_i$  from the set *T* according to a stationary rule.
- When the set {t<sub>i</sub>} is opened to manipulation during the data collection, it is an important experiment design issue to take appropriate sampling instants. Therefore,



Fig. 7. The relaxation modulus measurements  $\overline{G}(t_i)$  (points) and the approximate Maxwell models  $G_M(t, g_N)$  (solid line); random choice of the sampling instants

new deeper insight in the stress relaxation experiment can be achieved. The approach proposed lies, in fact, in widely understood data mining framework [15].

4. The paper is concerned with the Maxwell model but the proposed experiment design scheme can also be successfully applied to identification of generalized Kelvin-Voigt model of the creep compliance measurements obtained in creep test [14].

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#### O PLANOWANIU EKSPERYMENTU DLA IDENTYFIKACJI MODELU MAXWELLA NA PODSTAWIE TESTU RELAKSACJI NAPRĘŻĘŃ

Streszczenie. Przedmiotem pracy jest problem optymalnej, w sensie najmniejszej sumy kwadratów aproksymacji modułu relaksacji materiałów liniowo lepkosprężystych uogólnionym modelem Maxwella na podstawie zakłóconych pomiarów modułu relaksacji zgromadzonych w teście relaksacji naprężeń. Zaproponowano algorytm identyfikacji oparty o koncepcję odpowiedniej randomizacji punktów pomiarowych prowadzący do wyznaczenia modelu Maxwella o parametrach asymptotycznie niezależnych od punktów pomiarowych nawet wówczas, gdy rzeczywisty opis modułu relaksacji jest całkowicie nieznany. Przeprowadzono analizę zbieżności modelu dla dokładnych i zakłóconych pomiarów i wskazano na jego wykładniczą zbieżność. Dla pięcio-parametrowego modelu Maxwella podano wyniki eksperymentów numerycznych. Wyznaczono cztero-parametrowe modele Maxwella próbki buraka cukrowego i pokazano zbieżność ciągu parametrów modelu optymalnego.

Słowa kluczowe: test relaksacji naprężeń, model Maxwella, algorytm identyfikacji, planowanie eksperymentu
# On determination of the relaxation spectrum of viscoelastic materials from discrete-time stress relaxation data

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Summary. The paper deals with the problem of recovery of continuous relaxation spectrum of linear viscoelastic materials from discrete-time noise corrupted measurements of relaxation modulus obtained in stress relaxation test. The leastsquares problem of optimal approximation of the spectrum is solved based on the orthogonal series expansion. Hermite functions are used. Since the problem of relaxation spectrum identification is ill-posed, the inverse problem of Tikhonov regularization is used to guarantee the stability of the scheme. Guaranteed model approximation (GMA) is adopted for the choice of the regularization parameter. The numerical realization of the scheme by using the singular value decomposition (SVD) is discussed. The resulting identification algorithm is described in forthcoming paper.

K e y w o r d s : viscoelasticity, relaxation spectrum, identification, regularization, Hermite functions

## INTRODUCTION

Many materials are most often modelled in a timedomain viscoelastic regime, which is good for characterizing strain-stress dependence, creep and stress relaxation within a small deformation [1, 2, 4, 5, 7, 15, 16]. Although for viscoelastic materials a multiplicity of constitutive theories exists, essentially, only linear viscoelasticity is considered for which the Boltzmann superposition principle applies.

The mechanical properties of linear viscoelastic materials are characterized by relaxation spectrum [4, 5, 13, 16]. From the relaxation spectrum other material functions such as the relaxation modulus or the creep compliance can be calculated without difficulty and next both the constant and time-variable bulk and shear modulus or Poisson's ratio can be determined. Thus, the spectrum is vital not only for constitutive models but also for the insight into the properties of a viscoelastic material [13,19,27].

Relaxation spectrum is not directly accessible by experiment and thus must be determined from the appropriate response function, measured either in time or frequency domain [4, 13, 15, 27]. There are a few papers, e.g., [27] as well as [18-20] and the other previous papers by the present author cited therein, that deal with the relaxation spectrum determination from time-measurement data. However, the computationally efficient methods to determine the spectrum are still desirable and it is the purpose of this study.

The practical difficulty in the relaxation spectrum determination is rooted in a theoretical mathematical problem difficulty, because it is an ill-posed inverse problem [4,19]. The mathematical difficulties can be overcome by synthesis of an appropriate identification algorithm. In this paper an optimal scheme of the least-squares approximation of relaxation spectrum by the linear combination of Hermite functions is proposed. The assumed quality of the model approximation is achieved by the respective choice of the regularization parameter by using guaranteed model approximation rule.

#### RELAXATION SPECTRUM

In the rheological literature it is commonly assumed that the modulus G(t) has the following relaxation spectrum representation [5,16]:

$$G(t) = \int_{0}^{\infty} H(v) e^{-tv} dv, \qquad (1)$$

where: the relaxation spectrum H(v) characterizes the distribution of relaxation frequencies  $v \ge 0$  in the range [v,v+dv]. We assume that the real relaxation spectrum H(v) there exists – the respective existence and uniqueness conditions are given in [21; Part I: Theorem 1, Part II: Theorems 1, 2]. Throughout we shall be concerned with

the case when the spectrum H(v) is completely unknown; the relaxation modulus G(t) can be, however, measured for any time  $t \ge 0$ .

The problem of relaxation spectrum determination is the numerical problem of reconstructing solution of Fredholm integral equation of the first kind (1) from time-measured discrete relaxation modulus data. This problem is known by Hadamard to be severely ill-posed [19, 23]. This means that small changes in measurement data can lead to arbitrarily large changes in the relaxation spectrum. In remedy, some reduction of the admissible solutions set or respective regularization of the original problem can be used. In this paper we use both the techniques simultaneously. An approximation of the spectrum by the finite series of Hermite functions is combined with Tikhonov regularization.

The idea of the scheme is based on the Fourier series expansion of unknown relaxation spectrum with respect to the orthonormal basis in function space. This approach is known both in the approximation theory [25] and in mathematical modelling and system identification tasks [8,9,14]. A wide overview of the significance of the orthogonal basis in system identification is available in [14]. Orthogonal schemes are also used for signal processing [9] and in automatic control algorithms [3,26]. In the identification of mathematical models of viscoelastic material orthogonal series expansion approach is used both for linear materials, e.g., [15,19,20], and for nonlinear materials for example in [3]. The Hermite polynomials are applied for systems identification, for example in [6].

# MODELS

Assume that  $H(v) \in L_2(0,\infty)$ , where  $L_2(0,\infty)$  is the space of square-integrable functions on the interval  $(0,\infty)$ . The respective sufficient conditions are given in [21; Part II: Theorem 3]. Let  $h_k(v)$ ,  $k=0,1,\ldots$ ; let the Hermite functions be given by [12]:

$$h_{k}(\nu) = \frac{\sqrt{\alpha}}{\sqrt{2^{k} k!} \sqrt[4]{\pi}} e^{-(\alpha \nu)^{2}/2} P_{k}(\alpha \nu), \quad k = 0, 1, \dots,$$
(2)

where:  $P_k(x)$  is Hermite polynomial of degree k defined by recursive formula [12]:

$$P_k(x) = 2xP_{k-1}(x) - 2(k-1)P_{k-2}(x), \quad k = 2, 3, \dots, \quad (3)$$

starting with:

$$P_0(x) = 1 \text{ and } P_1(x) = 2x,$$
 (4)

where:  $\alpha > 0$  is a time-scaling factor.

We assume that the model of the relaxation spectrum is to be selected within the parametric class of models defined by the finite sum:

$$H_{K}\left(\nu\right) = \sum_{k=0}^{K-1} g_{k} h_{k}\left(\nu\right), \tag{5}$$

where:  $g_k$  are constant model parameters, the lower index of  $H_k(v)$  is the number of model summands. Then, the respective model of the relaxation modulus is described by:

$$G_{K}(t) = \int_{0}^{\infty} H_{K}(v) e^{-tv} dv = \sum_{k=0}^{K-1} g_{k} \phi_{k}(t), \qquad (6)$$

where, according to equation (1), the functions  $\phi_k(t)$  are defined as:

$$\phi_k\left(t\right) = \int_0^\infty h_k\left(v\right) e^{-tv} dv. \tag{7}$$

The useful recursive form of the basis functions  $\phi_k(t)$  is given by the following theorem; the proof, as well as the proofs of the next results, is omitted due to space limitations.

**Theorem 1.** Let  $\alpha > 0$  and  $t \ge 0$ . Then the basis functions  $\phi_k(t)$  (7) are given by the recursive formula:

$$\phi_{k+1}(t) = \frac{1}{\sqrt{2^{k-1}\alpha(k+1)!}} \frac{4}{\sqrt{\pi}} P_k(0) - \frac{\sqrt{2}}{\alpha\sqrt{k+1}} t \phi_k(t) + \frac{\sqrt{k}}{\sqrt{k+1}} \phi_{k-1}(t), \quad k \ge 1, \quad (8)$$

starting with:

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$$\phi_0(t) = \frac{\sqrt[4]{\pi}}{\sqrt{2\alpha}} e^{t^2/(2\alpha^2)} \operatorname{erfc}\left(t/(\sqrt{2}\alpha)\right), \qquad (9)$$

$$\phi_1(t) = \frac{\sqrt{2}}{\sqrt{\alpha}\sqrt[4]{\pi}} - \frac{\sqrt{2}}{\alpha} t \phi_0(t), \tag{10}$$



Fig. 1. The Hermite basis functions  $h_k(v)$  for parameters: (a)  $\alpha = 1[s]$  and (b)  $\alpha = 10[s]$ ; k = 0, 1, 2, 3, 4

where the function:

$$erfc(x) = \frac{2}{\sqrt{\pi}} \int_{x}^{\infty} e^{-t^2} dt, \quad x \ge 0,$$
(11)

is complementary error function [12].

The values  $P_{\mu}(0)$  of Hermite polynomials are given by:

$$P_{2k}(0) = (-1)^k (2k)!/k!$$
 and  $P_{2k+1}(0) = (0).$  (12)

A few first basis functions  $h_k(v)$  are shown in Figure 1 for two different values of the time-scaling factor  $\alpha$ ; the corresponding functions  $\phi_k(t)$  are plotted in Figure 2.

Note that from Figure 2 it is evident that the basis functions are congruent to the real relaxation modulus obtained in experiment. The parameter  $\alpha > 0$  is the timescaling factor. The following rule holds: the lower the parameter  $\alpha$  is, the shorter the relaxation times are, i.e. the greater are the relaxation frequencies. The above is illustrated by Figures 1 and 2. What must be done to salvage it is to find some way of determining the basis functions which 'look like' the real relaxation modulus. To further this end, we must choose the respective time scale factor  $\alpha$ .

#### AUGMENTED MODEL

It is well-known [5,16,19] that for many materials  $\lim_{t\to\infty} G(t) = G_{\infty} > 0$ , where  $G_{\infty}$  is the long-term modulus. It is also the case of the beet root sample, which is considered in [22; Example 3]. Thus, instead of the classical model (6), it is convenient to consider the following augmented model:

$$\overline{G}_{K}(t) = \int_{0}^{\infty} H_{K}(v) e^{-tv} dv + G_{\infty} = G_{K}(t) + G_{\infty}.$$
 (13)

Then, the relaxation spectrum model takes the form:

$$\bar{H}_{K}(\nu) = H_{K}(\nu) + G_{\infty}\delta(\nu), \qquad (14)$$

where:  $H_K(v)$  is given by (5) and  $\delta(v)$  denotes the Dirac delta function. Unbounded component  $G_{\infty}\delta(v)$  of the relaxation spectrum  $\overline{H}_K(v)$  (14) corresponds with the relaxation frequency equal to zero, or equivalently, with infinite relaxation time.

#### IDENTIFICATION PROBLEM

Classical manner of studying viscoelasticity is by two-phase stress relaxation test, where the time-dependent shear stress is studied for step increase in strain [16, 24]. In the first initial phase the strain should be imposed instantaneously. During the second phase the corresponding force induced in the specimen, which decreases with time, is measured.

Suppose a stress relaxation test performed on the specimen of the material under investigation resulted in a set of measurements of the modulus  $\overline{G}(t_i) = G(t_i) + z(t_i)$  at the sampling instants  $t_i \ge 0$ , i = 1, ..., N, where  $z(t_i)$  is measurement noise.

Identification consists of selection within the given class of models defined by (6), (13) of such a model, which ensures the best fit to the measurement results. As a measure of the model (6), (13) accuracy the square index commonly used in identification theory [6, 10, 19, 20] and experimental studies [11, 19, 20] is taken:

$$Q_{N}(\boldsymbol{g}_{K}) = \sum_{i=1}^{N} \left[ \overline{G}(t_{i}) - \overline{G}_{K}(t_{i}) \right]^{2} = \left\| \overline{\boldsymbol{G}}_{N} - \boldsymbol{\boldsymbol{\varphi}}_{N,K} \boldsymbol{g}_{K} \right\|_{2}^{2}, (15)$$

where:  $\|\cdot\|_2$  denotes the square norm in the Euclidean space,  $\boldsymbol{g}_K = [\boldsymbol{g}_0 \dots \boldsymbol{g}_{K-1} \boldsymbol{G}_{\infty}]$  is an (K+1) – element vector of unknown coefficients of the model (6), (13). The  $N \times (K+1)$ – element matrix  $\boldsymbol{\Phi}_{NK}$  and the vector  $\overline{\boldsymbol{G}}_N$  are defined as:

$$\boldsymbol{\varPhi}_{N,K} = \begin{bmatrix} \phi_0(t_1) & \dots & \phi_{K-1}(t_1) & 1 \\ \vdots & \ddots & \vdots & \vdots \\ \phi_0(t_N) & \dots & \phi_{K-1}(t_N) & 1 \end{bmatrix}, \qquad \boldsymbol{\bar{G}}_N = \begin{bmatrix} \boldsymbol{\bar{G}}(t_1) \\ \vdots \\ \boldsymbol{\bar{G}}(t_N) \end{bmatrix}. (16)$$

Thus, the optimal identification of relaxation spectrum in the class of functions  $\overline{H}_{K}(\nu)$  given by (5), (14) consists of solving, with respect to the model parameter  $g_{\kappa}$ , the least-squares problem with the index (15). The matrix  $\boldsymbol{\Phi}_{NK}$  is usually ill-conditioned. Then, the minimum of (15) is not unique and even the normal (minimum Euclidean norm) solution of the linear-quadratic problem (15)-(16) is non-continuous and unbounded function of the data vector  $\overline{\boldsymbol{G}}_{N}$ , i.e. when the data are noisy even small changes in  $\overline{\boldsymbol{G}}_{N}$  would lead to arbitrarily large artefact in  $\overline{\boldsymbol{g}}_{K}^{N}$ . This is a crucial point of the problem. To deal with the ill-posedness, the Tikhonov regularization method is used as presented in the subsequent section.



**Fig. 2.** Functions  $\phi_k(t)$  of Hermite algorithm, the parameters: (a)  $\alpha = 1[s]$  and (b)  $\alpha = 10[s]$ ; k = 0, 1, 2, 3, 4

#### REGULARIZATION

Tikhonov regularization [23] strives to stabilize the computation of the least-squares solution by minimizing a modified square functional of the form:

$$\min_{\boldsymbol{g}_{K} \in R^{K}} \left\| \overline{\boldsymbol{G}}_{N} - \boldsymbol{\varPhi}_{N,K} \boldsymbol{g}_{K} \right\|_{2}^{2} + \lambda \left\| \boldsymbol{g}_{K} \right\|_{2}^{2}, \quad (17)$$

where:  $\lambda > 0$  is a regularization parameter. The above problem is well-posed, that is the solution always exists, is unique, and continuously depends on both the matrix  $\boldsymbol{\Phi}_{N,K}$  as well as on the measurement data  $\overline{\boldsymbol{G}}_{N}$ . The model parameter vector minimizing (17) is given by:

$$\boldsymbol{g}_{K}^{\lambda} = \left(\boldsymbol{\varPhi}_{N,K}^{T} \; \boldsymbol{\varPhi}_{N,K} + \lambda \; \boldsymbol{I}_{K+1,K+1}\right)^{-1} \boldsymbol{\varPhi}_{N,K}^{T} \; \boldsymbol{\bar{G}}_{N}, \quad (18)$$

where:  $I_{K+1, K+1}$  is  $(K+1) \times (K+1)$  identity matrix.

The choice of regularization parameter  $\lambda$  is crucial to identify the best model parameters. Here we apply the guaranteed model approximation (GMA) rule, which is presented in details below. The choice of the regularization parameter according to GMA does not depend on *a priori* knowledge about the noise variance.

#### ALGEBRAIC BACKGROUND

For numerical computation of regularized solution (18), the singular value decomposition (SVD) technique will be used. Let SVD of the matrix of the matrix  $\boldsymbol{\Phi}_{N,K}$  take the form [17]:

$$\boldsymbol{\Phi}_{N,K} = \boldsymbol{U}\boldsymbol{\Sigma}\boldsymbol{V}^{T},\tag{19}$$

where:  $V \in \mathbb{R}^{K+1, K+1}$  and  $U \in \mathbb{R}^{N,N}$  are orthogonal matrices and  $\Sigma = diag(\sigma_1, ..., \sigma_r, 0, ..., 0)$  is  $N \times (K+1)$  diagonal matrix containing the non-zero singular values  $\sigma_1, ..., \sigma_r$  of the matrix  $\boldsymbol{\Phi}_{N,K}$  with  $r = rank(\boldsymbol{\Phi}_{K,K})$  [17]. Taking advantage of the diagonal structure of  $\Sigma$  and the matrices V and Uorthogonality, it may be simply proved that [19]:

$$\boldsymbol{g}_{K}^{\lambda} = \boldsymbol{V}\boldsymbol{\Lambda}_{\lambda}\boldsymbol{U}^{T}\boldsymbol{\overline{G}}_{N}, \qquad (20)$$

where: the diagonal structure matrix  $\Lambda_{i}$  is as follows:

$$\Lambda_{\lambda} = diag\left(\sigma_{1} / \left(\sigma_{1}^{2} + \lambda\right), \dots, \sigma_{r} / \left(\sigma_{r}^{2} + \lambda\right), 0, \dots, 0\right).$$
(21)

#### GUARANTEED MODEL APPROXIMATION

We wish to introduce a simple rule for the choice of the regularization parameter, in which the value of the identification index is directly taken into account. It may be proved that for an arbitrary  $\lambda > 0$  the following equality holds:

$$Q_N\left(\boldsymbol{g}_K^{\lambda}\right) = \sum_{i=1}^r \frac{\lambda^2 y_i^2}{\left(\sigma_i^2 + \lambda\right)^2} + Q_N\left(\overline{\boldsymbol{g}}_K^N\right), \quad (22)$$

where:  $\boldsymbol{g}_{K}^{N}$  of the normal solution of the least-squares task (15)-(16) for noise-free data  $G_N = [G(t_1) \dots G(t_N)]$ and  $y_i$  are the elements of the vector  $\boldsymbol{Y} = \boldsymbol{U}^T \boldsymbol{\overline{G}}_N$ . Hence  $Q_N(\mathbf{g}_K^{\lambda}) > Q_N(\overline{\mathbf{g}}_K^N)$ . The deterioration of the model quality is a result of the stabilization of the linear leastsquares task (15). However, the assessment of model quality is typically based on how the model performs when it attempts to reproduce the measured data. This is the viewpoint we are going to adopt. Focusing then more on the model quality in this section we shall introduce the guaranteed model approximation (GMA) rule of the choice of the regularization parameter. Some of its properties will also be demonstrated. The idea behind GMA rule is to choose the regularization parameter so that the assumed quality of the model approximation index  $\hat{Q}_N > Q_N(\overline{g}_K^N)$  is achieved, i.e., such a parameter  $\hat{\lambda}$  for which  $Q_N(\boldsymbol{g}_K^{\hat{\lambda}}) = \hat{Q}_N$ . Appealing to the equation (22) this rule consists in solving - with respect to  $\lambda$  – of the following equation:

$$\sum_{i=1}^{r} \frac{\lambda^2 y_i^2}{\left(\sigma_i^2 + \lambda\right)^2} + Q_N\left(\overline{\boldsymbol{g}}_K^N\right) = \hat{Q}_N, \qquad (23)$$

where:  $Q_N(\overline{g}_K^N) = \sum_{i=r+1}^N y_i^2$ . The GMA rule was at first applied for the relaxation times spectrum identification in early authors' work [18]. This rule seems to be quite a natural strategy in the context of relaxation spectrum identification task in which the identification index refers to the relaxation modulus approximation quality. Note that if there exists an  $1 \le i \le r$  such that  $y_i \ne 0$ , then the quality index  $Q_N(g_K^\lambda)$  is monotonically increasing function of  $\lambda > 0$  (compare eq. (22)). Thus, the equation (23) has a unique solution  $\hat{\lambda} > 0$  whenever  $\hat{Q}_N > Q_N(\overline{g}_K^N)$  and there exists  $y_i \ne 0$ ,  $1 \le i \le r$ . Simple *a posteriori* criteria for when the last condition is satisfied are given by the following corollary proved in [19; Property C.1].

**Corollary.** Let  $K \ge 1$ ,  $r = rank(\Phi_{N,K}) < N$  and  $N \ge K$ . If so, there exists an  $1 \le i \le r$  such that  $y_i \ne 0$  if and only if  $\Phi_{N,K}^{T} \overline{G}_N \ne \mathbf{0}_{K+1}$ , where  $\mathbf{0}_{K+1}$  denotes (K+1)-vector of zero elements.

Thus, we now have a more convenient way of characterizing when the solution of GMA rule exists, since the SVD decomposition of the matrix  $\boldsymbol{\Phi}_{N,K}$  is not required here.

Both the function:

$$F\left(\lambda, \boldsymbol{\Sigma}, \boldsymbol{Y}\right) = \sum_{i=1}^{r} \frac{\lambda^{2} y_{i}^{2}}{\left(\sigma_{i}^{2} + \lambda\right)^{2}} + Q_{N}\left(\overline{\boldsymbol{g}}_{K}^{N}\right) - \hat{Q}_{N}, (24)$$

and the derivative:

$$F_{\lambda}'(\lambda, \boldsymbol{\Sigma}, \boldsymbol{Y}) = 2\lambda \sum_{i=1}^{r} \frac{y_i^2 \sigma_i^2}{\left(\sigma_i^2 + \lambda\right)^3},$$
(25)

can be expressed by convenient formulas as functions of singular values  $\sigma_1, ..., \sigma_r$  and elements  $y_i$  of the vector *Y*. Thus, in order to find a solution  $\hat{\lambda}$  of equation (23), i.e.  $F(\hat{\lambda}, \boldsymbol{\Sigma}, \boldsymbol{Y}) = 0$ , the Newton scheme can be successfully applied, in which the successive approximation of the regularization parameter  $\hat{\lambda}$  is computed according to the formula:

$$\lambda_{n+1} = \lambda_n - \frac{F(\lambda_n, \boldsymbol{\Sigma}, \boldsymbol{Y})}{F'_{\lambda}(\lambda_n, \boldsymbol{\Sigma}, \boldsymbol{Y})}.$$

An arbitrary  $\lambda_0 \neq 0$  can be taken as an initial point. The functions  $F(\lambda, \Sigma, Y)$  (24) and  $F'_{\lambda}(\lambda, \Sigma, Y)$  (25) depend continuously on every argument. Thus, on the basis of the well-known implicit function theorem the solution  $\lambda = \hat{\lambda}(\Sigma, Y)$  is continued with respect to the matrix  $\Sigma$  and vector Y. Thus, the above GMA rule is well-posed in the Hadamard sense.

A certain interpretation of the GMA rule and important property of the solution:

$$\hat{\boldsymbol{g}}_{K} = \boldsymbol{g}_{K}^{\lambda} \tag{26}$$

are given in the following result. The conclusion follows immediately from a quick inspection of the proof of [18; theorem 2].

**Theorem 2.** Assume  $K \ge 1$ ,  $N \ge K$  and  $\hat{Q}_N > Q_N(\overline{g}_K^N)$ . The regularized solution  $\hat{g}_K$  defined by (23) and (26) is the unique solution of the following optimization task:

$$\min_{\boldsymbol{g}_{K} \in \mathbb{R}^{K}} \|\boldsymbol{g}_{K}\|_{2}^{2} \text{ under the constraint } Q_{N}\left(\boldsymbol{g}_{K}^{\lambda}\right) \leq \hat{Q}_{N}.$$

By theorem 2 the GMA rule (23) relies in such a selection of the relaxation spectrum model that the norm of the vector  $\hat{g}_{\kappa}(26)$  has the smallest possible value among all models such that  $Q_{N}(g_{\kappa}) \leq \hat{Q}_{N}$ . Thus the best smoothness of the model parameters vector  $\hat{g}_{\kappa}(26)$  is achieved. The effectiveness of this approach in the context of relaxation spectrum identification has been verified by the earlier authors' works, see [18, 19].

#### CONCLUSIONS

The problem of the relaxation spectrum calculation from discrete-time linear relaxation modulus noise data is solved based on the least-squares approximation of the spectrum by finite linear combination of the basic Hermite functions. As a result, the primary infinite dimensional dynamic optimization problem of the continuous relaxation spectrum identification is reduced to the static linear-quadratic programming task. Tikhonov regularization and guaranteed model approximation are used to solve it. The analysis of the scheme stability, noise robustness, smoothness and convergence as well as simulation tests using both artificial and experimental data are the subject of the next paper [22].

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# O IDENTYFIKACJI SPECTRUM RELAKSACJI MATERIAŁÓW LEPKOSPRĘŻYSTYCH NA PODSTAWIE DYSKRETNYCH POMIARÓW MODUŁU RELAKSACJI

Streszczenie. Praca dotyczy problemu wyznaczania ciągłego spektrum relaksacji materiałów o własnościach liniowolepkosprężystych na podstawie dyskretnych zakłóconych pomiarów modułu relaksacji uzyskanych w teście relaksacji naprężeń. Problem rozwiązano przybliżając spektrum relaksacji skończonym szeregiem funkcji Hermita optymalnie w sensie zregularyzowanej metody najmniejszej sumy kwadratów. Zastosowano regularyzację Tichonowa. Współczynnik regularyzacji dobrano metodą gwarantowanej jakości modelu (ang. guaranteed model approximation). Odpowiedni algorytm identyfikacji będzie przedmiotem następnej pracy.

Słowa kluczowe: lepkosprężystość, spectrum relaksacji, identyfikacja modelu, regularyzacja, funkcje Hermita.

# On measurement point-independent identification of maxwell model of viscoelastic materials

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S u m m a r y. The problem of a weighted least-squares approximation of viscoelastic material by generalized Maxwell model is discussed when only the noise-corrupted time-measurements of the relaxation modulus are accessible for identification. To build a Maxwell model, which does not depend on sampling instants is a basic concern. It is shown that even when the true relaxation modulus description is completely unknown, the approximate optimal Maxwell model parameters can be derived from the measurement data sampled randomly according to appropriate randomization. The determined approximate model is a strongly consistent estimate of the requested model. An identification algorithm leading to the best model will be presented in the forthcoming paper, in which the convergence analysis will be also conducted. A motivating example is given.

Key words: viscoelasticity, relaxation modulus, Maxwell model, model identification

# INTRODUCTION

Viscoelastic materials present a behaviour that implies dissipation and storage of mechanical energy. Viscoelastic models are used before all to modelling of different polymeric liquids and solids [3, 6, 14], concrete [1], soils [13], rubber [30], glass [5, 23], foods [2, 20, 22, 24]. Research studies conducted during the past few decades proved that these models are also an important tool for studying the behaviour of biological materials: wood [28], fruits, vegetables [8, 10, 11, 20], animals tissues [16], see also other papers cited therein.

Viscoelasticity of the materials manifests itself in different ways, such as gradual deformation of a sample of the material under constant stress (creep behaviour), and stress relaxation in the sample when it is subjected to a constant strain [6, 20, 29]. In general, viscoelasticity is a phenomenon associated with time variations in a material's response. In an attempt to describe some of the above effects mathematically several constitutive laws have been proposed which describe the stress–strain relations in terms of quantities like creep compliance, relaxation modulus, the storage and loss moduli and dynamic viscosity. Some of these constitutive laws have been developed with the aid of mechanical models consisting of combinations of springs and viscous dashpots. The Maxwell model is, perhaps, the most representative example of such models.

The classical Maxwell model is a viscoelastic body that stores energy like a linearized elastic spring and dissipates energy like a classical fluid dashpot. Within the past 40 years, advances in the Maxwell model study in the area of viscoelactic materials have been of three types. First the analysis of viscoelastic properties of such materials, e.g. elasticity, viscosity on the basis of Maxwell model, for example for polymers [3, 14], foods [2, 4, 20, 22, 24], biological materials [8, 9, 16], soda-lime-silica glass [5]. Next, the application of Maxwell model to compute other material functions such as the creep compliance, time-variable bulk and shear modulus or time-variable Poisson's ratio [27] or interconversion between linear viscoelastic material functions [19]. And finally, the development of computational tools for Maxwell model determining [21, 30]. This paper belongs to the latter group.

We often determine the parameters in a model by obtaining the "best-possible" fit to experimental data. The coefficients can be highly dependent on our way of measuring "best" [17]. Common choice of the model quality measure is the mean square approximation error, leading to a least-squares identification problem. When the identification index is fixed, the coefficients can be also highly dependent on the measurement data. To make the idea a little clear we give an example of the fourparameter Maxwell model determination of an confined cylindrical specimen of the beet sugar root.

To build a Maxwell model, which does not depend on sampling instants is a basic concern. We consider the problem of measurement point-independent approximation of a linear relaxation modulus of viscoelastic material within the class of discrete generalized Maxwell models when the integral weighted square error is to be minimized and the true material description is completely unknown. We show how the problem can be solved by introducing an appropriate randomization on the set of sampling instants at which the relaxation modulus of the material is measured. It is assumed that only the relaxation modulus measurements are accessible for identification. The idea of measurement point-independent identification was at first used for noiseless zero-memory system approximation by random choice of inputs in co-author paper [12].

## IDENTIFICATION OF THE MAXWELL MODEL

#### MATERIAL

We consider a linear viscoelastic material subjected to small deformations for which the uniaxial, nonaging and izotropic stress-strain equation can be represented by a Boltzmann superposition integral [6]:

$$\sigma(t) = \int_{-\infty}^{t} G(t-\lambda)\dot{\varepsilon}(\lambda) \, d\lambda \,, \tag{1}$$

where:  $\sigma(t)$  and  $\varepsilon(t)$  denotes the stress and stain, respectively, and G(t) is the linear time-dependent relaxation modulus. The modulus G(t) is the stress, which is induced in the viscoelastic material described by equation (1) when the unit step strain  $\varepsilon(t)$  is imposed.

By assumption, the exact mathematical description of the relaxation modulus G(t) is completely unknown, but the value of G(t) can be measured with a certain accuracy for any given value of the time t $\in$ T, where T=[0,T] and  $0 < T < \infty$  or T= $R_+$ ; here  $R_+$ =[0, $\infty$ ).

#### MAXWELL MODEL

The generalized discrete Maxwell model, which is used to describe the relaxation modulus G(t), consists of a spring and *n* Maxwell units connected in parallel as illustrated in Figure 1. A Maxwell unit is a series arrangement of the Hooke and Newton's elements: an ideal spring in series with a dashpot. This model presents a relaxation of exponential type given by a finite Dirichlet-Prony series [29]:

$$G_M(t, \boldsymbol{g}) = \sum_{j=1}^n E_j e^{-\nu_j t} + E_{\infty},$$
(2)

where:  $E_j$ ,  $v_j$  and  $E_{\infty}$  represent the elastic modulus (relaxation strengths), relaxation frequencies and equilibrium modulus (long-term modulus), respectively. The vector of model (2) parameters is defined as:

$$\boldsymbol{g} = [E_1 \dots E_n \quad v_1 \dots v_n \quad E_{\infty}]^T. \tag{3}$$

The modulus  $E_j$  and the viscosity  $\eta_j$  associated with the *j*-*th* Maxwell mode (see Figure 1) determine the relaxation frequency  $v_j = E_j/\eta_j$ .



Fig. 1. Generalized discrete Maxwell model with additional elastic element  $E_{\infty}$  (Zeners' model)

It is not assumed that the real relaxation modulus G(t) can be exactly represented within the chosen set of models (2), (3). The restriction that the model parameters are nonnegative and bounded must be given to satisfy the physical meaning, i.e.  $g \in G$ , where the admissible set of parameters G is compact subset of the space  $R_{+}^{2n+1}$ .

#### IDENTIFICATION OF THE MAXWELL MODEL

A classical manner of studying viscoelasticity is by two-phase stress relaxation test, where the time-dependent shear stress is studied for step increase in strain [20, 29]. Suppose, a certain stress relaxation test performed on the specimen of the material under investigation resulted in a set of measurements of the relaxation modulus  $\overline{G}(t_i) = G(t_i) + z(t_i)$  at the sampling instants  $t_i \ge 0$ , i=1,...,N, where  $z(t_i)$  is measurement noise. Identification consists of selecting within the given class of models (2), (3) such a model, which ensures the best fit to the measurement results. As a measure of the model (2) accuracy the mean sum of squares is taken:

$$Q_N(\boldsymbol{g}) = \frac{1}{N} \sum_{i=1}^{N} \left[ \overline{G}(t_i) - G_M(t_i, \boldsymbol{g}) \right]^2.$$
(4)

This is the least-squares criterion for Maxwell model. Therefore the least-squares Maxwell model identification consists of determining the parameter gN minimizing the index (4) on the set G by solving the following optimization problem:

$$Q_N(\boldsymbol{g}_N) = \min_{\boldsymbol{g} \in \boldsymbol{G}} Q_N(\boldsymbol{g}).$$
(5)

Exponential sum models are used frequently in applied research: time series in economics, biology, medicine, heat diffusion and diffusion of chemical compounds in engineering and agriculture, physical sciences and technology, see, e.g., [7, 18]. Fitting data to exponential sums is a very old problem, which has been studied for a long time. Several articles have appeared mainly to finding optimal least-squares exponential sum approximations to sampled data. Holmström and Petersson [15] have reviewed known algorithms in much detail.

The results of identification, both the model parameters and the resulting relaxation modulus are (strongly) dependent on the measurement data, in particular of the sampling instants  $t_i$ . This is best illustrated by an example.

#### EXPERIMENT AND MOTIVATING EXAMPLE

A cylindrical sample of 20 mm diameter and height was obtained from the root of sugar beet Janus variety [9]. During the two-phase stress relaxation test performed by Gołacki and co-workers at the University of Life Sciences in Lublin [9], in the first initial phase the strain was imposed instantaneously, the sample was preconditioned at the 0.5 m·s<sup>-1</sup> strain rate to the maximum strain. Next, during the second phase at constant strain the corresponding time-varying force induced in the specimen was recorded during the time period [0,100] seconds in 40000 measurement points with the constant sampling period  $\Delta t = 0.0025$ s. The experiment was performed in the state of uniaxial deformation; i.e. the specimen examined underwent deformation in steel cylinder (for details see, for example, [9]). The modelling of mechanical properties of this material in linear-viscoelastic regime is justified by the research results presented in a lot of works, for example [8]. For initial filtering of the force measurement data Savitzky-Golay method has been used. Next, the respective relaxation modulus measurements were computed using a simple modification of the well-known Zapas and Craft [29] rule:

$$\overline{G}(t) = \overline{F}(t + t_{m,real}/2)/(\varepsilon_0 p) \quad for \quad t \ge t_{m,real}/2,$$

where:  $t_{m,real}$  is the real time under which the induced force  $\overline{F}(t)$  take the maximum value,  $\varepsilon_0$  is the constant strain kept during the second phase of the test and p is the cross-section of the sample.

**Table 1.** Maxwell model (6) parameters and the values of identification index  $Q_N(g_N)$ ; equidistant-experiment

		Model par	Model parameters				
N	$Q_N(\boldsymbol{g}_N)$	<i>Е</i> <sub>1,N</sub> [MPa]	<i>Е</i> <sub>2,N</sub> [MPa]	$v_{1,N}[s^{-1}]$	$v_{2,N}$ [s <sup>-1</sup> ]		
15	0,0025	10,563	3,9242	8,6049E-4	1,7521		
20	0,0011	10,5135	3,8923	7,8748E-4	0,6296		
25	0,0021	10,5368	3,8794	8,1408E-4	0,7776		
40	0,0025	10,5372	3,9074	8,0998E-4	1,171		
50	0,0029	10,5515	3,9133	8,3473E-4	1,4523		
75	0,0032	10,5604	3,9521	8,4544E-4	2,1065		
100	0,0037	10,5596	3,9946	8,4957E-4	2,6723		
150	0,004	10,567	4,1043	8,5423E-4	4,2195		
200	0,0044	10,5664	4,2017	8,5543E-4	5,4635		
250	0,0042	10,5721	4,2935	8,6228E-4	6,7021		
300	0,0047	10,5716	4,438	8,6447E-4	8,4651		
350	0,0047	10,5733	4,483	8,6492E-4	9,0439		
400	0,0046	10,5717	4,6187	8,6186E-4	10,6006		
500	0,0046	10,5746	4,8924	8,6621E-4	13,7081		
600	0,0048	10,5747	5,0389	8,6689E-4	15,2986		

For *N* from the set  $N = \{15,20,25,40,50,75,100,150,200,250,300,350,400,500,600\}$  equidistant sampling points  $t_i$  have been taken in time interval [0,95] seconds, successively, and the respective relaxation modulus measurements have been selected from the whole set of measurement data. Next, the Levenberg-Marquardt optimization procedure was applied to solve the optimization task (5) and the four parameter Maxwell models:

$$G_M(t) = E_1 e^{-\nu_1 t} + E_2 e^{-\nu_2 t}, \tag{6}$$

where the elastic modulus  $E_i$  and the relaxation frequencies  $v_i$ , i=1,2, were determined for each N. The results of the identification, i.e. the optimal model parameters and the optimal values of the empirical index  $Q_N(\mathbf{g})$  are given in Table 1.



**Fig. 2.** (a) The distance  $d_N$  between the two successive Maxwell model parameters  $g_N$  and (b) the identification index  $Q_N(g_N)$  as a function of the number of measurements N; equidistant-experiment

To illustrate the convergence of the Maxwell model parameters in Figure 2(a) the distance  $d_N = ||\mathbf{g}_N - \mathbf{g}_{[N]}||_2$ , where [N] is a direct predecessor of N in the set N, is shown as a function of N; here  $|| \cdot ||_2$  denotes the Euclidean norm in the space  $R^{2n+1}$ . The course of the model quality index as a function of N is illustrated in Fig. 2(b). The relaxation modulus computed according to the best 'equidistant' Maxwell models  $G_M(t, \mathbf{g}_N)$  are plotted in Figure 3 for a few values of the number of measurements, where the measurements  $\overline{G}(t_i)$  are also marked. However, the models  $G_M(t, \mathbf{g}_N)$  does not differ significantly (see Figure 3), the model parameters differ essentially - compare Figure 2(a) and Table 1

The above example illustrates that the Maxwell model parameters will be highly dependent on the measurement data, if the sampling instants  $t_i$  are inappropriately chosen. This is a crucial point of the problem. Loosely speaking, the problem is, whether the identification procedure will

yield a Maxwell model parameters which are asymptotically (when the number of measurements tends to infinity) independent on the particular sampling instants. The issue involves aspects on whether the data set (i.e. the experimental conditions) is informative enough to guarantee this convergence result. We show, that this problem can be satisfactorily solved by introducing a simple randomization on the sampling times set.

#### METHODS AND RESULTS

# OPTIMAL APPROXIMATION OF THE MAXWELL MODEL

As a measure of the model (2), (3) accuracy the global approximation error of the form:

$$Q(\mathbf{g}) = \int_{\mathcal{T}} \left[ G(t) - G_M(t, \mathbf{g}) \right]^2 \rho(t) dt, \qquad (7)$$

where a chosen weighting function  $\rho(t) \ge 0$  is a density on T, i.e.,  $\int_{T} \rho(t) dt = 1$ , can be taken. Thus, the problem of the real relaxation modulus G(t) optimal approximation within the class of Maxwell models reduces, obviously, to determining the parameter  $g^*$  minimizing the index Q(g)on the set of admissible parameters G, i.e. takes the form:

$$\boldsymbol{g}^* = \arg\min_{\boldsymbol{g} \in \mathcal{G}} \mathcal{Q}(\boldsymbol{g}), \tag{8}$$

where  $\arg \min_{g \in G} Q(g)$  denotes the vector g that minimizes Q(g) on the set G. Note, that the empirical index  $Q_N(g)$  (4) is obtained by the replacement of the integral in Q(g) with the finite mean sum of squares.

#### MATHEMATICAL BACKGROUND AND ASSUMPTIONS

Let  $T_1,...,T_N$  are independent random variables with a common probability density function  $\rho(t)$  whose support is T. Let  $G_i = G(T_i)$  be the corresponding relaxation modulus, i = 1,...,N, and let  $\overline{G}_i = G_i + Z_i = G(T_i) + Z_i$  denote



Fig. 3. The relaxation modulus measurements  $\overline{G}(t_i)$  (points) and the approximate Maxwell models  $G_M(t, g_N)$  (solid line); equidistant-experiment

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their measurements obtained in a certain stress relaxation test performed on the specimen of the material under investigation. Here  $Z_i$  are additive measurement noises.

We take the following assumptions, which seems to be quite natural in the context of relaxation modulus approximation task.

- Assumption 1. The relaxation modulus G(t) is bounded on T, i.e. sup<sub>t∈T</sub>G(t)≤M<∞</li>
- Assumption 2. The set of admissible model parameters G is compact in the space  $R_+^{2n+1}$ .
- Assumption 3. The measurement noises Z<sub>i</sub> are bounded, i.e. |Z<sub>i</sub>|≤δ<∞ for i=1,...,N.</li>
- Assumption 4.  $\{Z_i\}$  is a time-independent sequence of independent identically distributed (i.i.d.) random variables with zero mean and a common finite variance  $\sigma^2$ :  $E[Z_i]=0$  and  $E[Z_i]=\sigma^{2}<\infty$ .

Note that the assumption 1 is satisfied, in particular, if  $G(0) < \infty$  and the weak energy dissipation principle is satisfied – for details see, for example [25]. Obviously, from assumption 4 if follows that  $E[G(T_i)+Z_i - G_M(T_i, \mathbf{g})] = Q(\mathbf{g}) + \sigma$ . Taking into account the Maxwell model equations (2), (3) set-up we see that the following properties hold.

- Property 1. G<sub>M</sub>(t,g) is continuous and differentiable with respect to g for any t∈T.
- Property 2. sup<sub>t∈T,g∈G</sub> ||∇gG<sub>M</sub>(t,g)||<sub>2</sub> <∞ for an arbitrary compact subset G of R<sup>2n+1</sup><sub>+</sub>.
- Property 3. sup<sub>t∈T,g∈G</sub>G<sub>M</sub>(t,g)<∞ for an arbitrary compact subset G of the space R<sup>2n+1</sup><sub>+</sub>.

Notice that, since in view of Property 1 the quality indices Q(g) and  $Q_N(g)$  are continuous with respect to g, then if the set G is compact in the space  $R_+^{2n+1}$ , the solutions of the optimal approximation tasks (5) and (8) there exist, on the basis of the well-known Weierstrass's theorem which asserts the existence of continuous function extrema on compact sets.

# ASYMPTOTIC PROPERTIES OF THE OPTIMAL MODEL

Now we wish to investigate the stochastic-type asymptotic properties of the Maxwell model approximation tasks (5) and (8). When studying these issues, the following proposition is instrumental.

• **Proposition 1.** When the relaxation modulus measurements are corrupted by additive noise and the Assumptions 1-4 are satisfied, then:

 $\sup_{\mathbf{g}\in \mathcal{G}} \left| \mathcal{Q}(\mathbf{g}) + \sigma^2 - \mathcal{Q}_N(\mathbf{g}) \right| \to 0 \quad w.p.1 \quad as \quad N \to \infty, (9)$ 

where w.p.1 means "with probability one".

The proof follows immediately from Property 2 in [12]. To verify this claim we need only note that the above Properties 1 and 2 guarantee that the assumptions A2 and A3 in [12] are satisfied. Next, the Assumption 2 is equivalent to A1, the Assumption 4 is equivalent to A5 ibidem, and due to Assumption 1 and Property 3 the assumption A4 ibidem holds.

Proposition 1 enables us to relate the Maxwell model parameter  $g_N$  solving the optimal approximation task (5) for empirical index  $Q_N(g)$  to the parameter  $g^*$  minimizing the deterministic function  $Q_N(g)$  in (8). Namely, from the uniform in  $g \in G$  convergence of the index  $Q_N(g)$  in (9) we conclude immediately the following.

 Proposition 2. Assume that Assumptions 1-4 are in force, T<sub>1</sub>,...,T<sub>N</sub> being independently, at random selected from T, each according to probability distributions with density ρ(t). Then for the additive noise corrupted relaxation modulus measurements:

$$\boldsymbol{g}_N \to \boldsymbol{g}^* \qquad w.p.1 \quad as \quad N \to \infty$$
 (10)

and for all  $t \in T$ :

$$G_M(t, \boldsymbol{g}_N) \to G_M(t, \boldsymbol{g}^*) \qquad w.p.1 \quad as \quad N \to \infty.$$

Thus, under the taken assumptions the Maxwell model parameter  $g_N$  is strongly consistent estimate of the parameter  $g^*$ . Moreover, since the Maxwell model  $G_M(t,g)$  is Lipschitz on G uniformly in  $t \in T$  (the above is guaranteed by Property 2), then the almost sure convergence of  $g_N$  to the respective parameter  $g^*$  in (10) implies that:

$$\sup_{t\in\mathcal{T}} \left| G_M(t, \boldsymbol{g}_N) - G_M(t, \boldsymbol{g}^*) \right| \to 0 \qquad w.p.1 \quad as \quad N \to \infty,$$

i.e.,  $G_M(t, \boldsymbol{g}_N)$  is in the case considered a strongly uniformly consistent estimate of the best model  $G_M(t, \boldsymbol{g}^*)$ .

# CONCLUSIONS

Summarizing, when the Assumptions 1-4 are satisfied, the arbitrarily precise approximation of the optimal Maxwell model (with the parameter  $g^*$ ) can be obtained (almost everywhere) as the number of measurements Ngrows large, despite the fact that the real description of the relaxation modulus is completely unknown. Thus, when the set  $\{t_i\}$  is open to manipulation during the data collection, it is an important experiment design issue to take an appropriate sampling instants. We shall comment on how to do this in the forthcoming paper [26], where the complete identification algorithm providing the strongly consistent estimate of the optimal model is given. The stochastic-type convergence analysis is also performed in [26] and the rate of convergence is discussed for the case when the measurements are perfect or corrupted by additive noises.

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# O NIEZALEŻNEJ OD PUNKTÓW POMIAROWYCH IDENTYFIKACJI MODELU MAXWELLA MATERIAŁÓW LEPKOSPRĘŻYSTYCH

Streszczenie. Rezultat identyfikacji, czyli wyznaczony model zależy zarówno od przyjętej klasy modeli oraz przyjętego wskaźnika jakości modelu, jak i konkretnych danych pomiarowych. W pracy rozważa się problem optymalnej w sensie najmniejszej sumy kwadratów aproksymacji modułu relaksacji materiałów liniowo lepkosprężystych uogólnionym modelem Maxwella na podstawie dyskretnych, zakłóconych pomiarów modułu relaksacji zgromadzonych w teście relaksacji naprężeń. Zakłada się, że opis rzeczywistego modułu relaksacji jest całkowicie nieznany. Pokazano, że wprowadzając odpowiednia randomizację punktów pomiarowych można uzyskać model Maxwella asymptotycznie niezależny od punktów pomiarowych. Wyznaczony model jest silnie zgodnym estymatorem modelu optymalnego w sensie całkowego kwadratowego wskaźnika jakości niezależnego od punktów pomiarowych. Odpowiedni algorytm identyfikacji będzie przedmiotem ko-lejnej pracy, w której przeprowadzona zostanie także analiza model Maxwella, identyfikacja modelu. zbieżności modelu.

Słowa kluczowe: lepkosprężystość, moduł relaksacji,

# Production and technical potential of farms united in the selected producer group<sup>1</sup>

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Summary. The purpose of this work was to carry out an analysis of the production size and direct outlays connected with it according to the gross margin balance index, the mean value of which amounted to 38.96 thousand PLN·ha-1AL. Moreover, equipment of the technical base of the producer group which aims at fruit production was described. The obtained data allow for the conclusion that in the case of the researched farms, there are no essential differences in the quantity equipment of the machinery park, which is selected according to the carried out agricultural production. The planned technical investments performed within the plan of the group, in order to be accepted assume purchase of machines and devices, which improve the quality of the production. In the case of the researched group, the most significant investment is construction of a cold storage of 1300 t of load capacity and purchase of an electronic line for fruit sorting of approx. 4 t-ha-1 productivity.

Key words: agricultural production, machinery park, agricultural farm, producer group

#### INTRODUCTION

Along with Poland's accession to the European Union, the membership on the European market created many development opportunities, e.g. access to the union funds or European consumers. On the other hand, it became a great challenge for Polish entrepreneurs, since it meant that Poland would have to adjust the legal requirements and deal with competition on the uniform inner market of the European Union [12]. Polish farms, in order to carry out the above mentioned tasks should be equipped with modern technical base, without which it is impossible to increase the plant and animal production [2,14, 16]. Proper organisation of transport has a significant meaning from the plant production point of view through an optimal selection of transport means [9]. An old machinery park and a low degree of its use limit mechanisation development, while it should be developed rather than limited. It is due to extending the periods of machine use over the catalogue norms, which results in frequent failures of a machinery park and increasing changeable costs incurred on restorations and repairs [6]. Forming suitable agricultural organisations is an alternative for fragmented individual farms, which want to be significant on the European market [14]. A producer group is an agreement between people who operate together, in order to increase incomes and lower production costs and to convince that common marketing is the best way to increase a market position of farms [5]. Small and individual farms have more difficulties in remaining on the European market since incomes from the agricultural activity cannot cover the costs of purchase of modern equipment or modernisation of an old technical base [14, 7]. It is also more difficult for individual farms to strengthen their position on the European market, since they are not able to supply large uniform parts of products on time, which results from the lack of suitable machines and technologies. Except for large parts and continuity of supplies, this product should be of high quality in order to meet the recipients' demands [13]. Only implementation of modern technologies, machines and devices as well as suitable storage base may ensure the above mentioned demands [8]. Farms, which will potentially develop and which obtain incomes allowing an access to new technologies, due to which technical progress will occur in a farm, should carry out the modernisation process [11,13]. Newer sets of tools, machines and even technological lines enter the market every year. However, only skilful use may influence modernisation of Polish farms and adjusting to proper agro- and zoo-technical activities will bring expected results. Modernisation of a farm which will potentially develop should last few years so that it may balance its

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production and accept a new situation [4]. The majority of Polish farms have an old and exploited machinery park, due to which management effects are unsatisfactory. Thus, it is so important nowadays to modernize farms so that they may carry out balanced and low-energy consuming agricultural production [15]. Meeting the challenges of the European Union markets is possible through recommendation of agricultural farms and uniting farmers [5]. Upon Poland's accession to the European Union, aid funds which are granted to farmers within forming groups of agricultural producers have increased. Due to the amendments to the Act on Groups of Agricultural Producers of 18 June 2004, not only natural persons could enter the group as it has been so far, but also persons carrying out or not carrying out a legal personality. It was a stimulus which resulted in the increase of groups of agricultural producers, which was also influenced by a decreased number of members composing the group, a decrease from 10 to 5 members [10]. The review of literature concerning the issue of the equipment level of a technical base in Polish agriculture in the aspect of production efficiency, allows to precisely define the objective of the work that is an analysis of technical base modernisation in the group of producers which produce fruit. In order to fully carry out the objective of the work, analysis of the land resources and seize of production was carried out. The scope of the work covered the group of apple producers. This group associates 6 agricultural producers. An analysis of results was carried out for their farms as individual facilities and the group as a formalised form of cooperation of agricultural producers.

# MATERIALS AND METHODS

In order to determine efficiency of activity in the researched facilities, the gross margin was calculated and economic size of farms was estimated.

**Gross margin** (*NB*) was calculated according to the following formula:

$$NB = PK_{hrutto} - KB_{m-s} + SU \quad [tys.zl \cdot ha^{-1}UR]$$

where:  $PK_{gross}$  - annual value of the gross final production obtained from animal and plant production,

 $KB_{ms}$  - direct costs incurred on production,

SU - union subvention in direct subsidies [1].

A tractor- machinery park of the researched farms was presented by calculating the following: quantity equipment of a technical base, replacement value of a machinery park, energy saturation index and by describing farm tractors (giving their number and age). The accepted research methodology according to the accepted assumptions was composed of two independent stages, that is: - the first stage assumed direct interviews in the group of producers with a managing team of the producer group, the second stage consisted in carrying a guided interview with farmers united in the researched group. As a result of the interviews carried out directly in the producer group, suitable lists including realisation of an investment were presented, which according to the principles of the Union subventions have to be included in the acceptance plan.

#### RESEARCH RESULTS, DISCUSSION

The level of equipment of the machinery park in the researched group has been presented in Table 1. Each farm has at least one basic machine. There are few machines, with which half of farms is equipped, that is: a planting auger, a pile driver, a mower-shredder. Moreover, there are few farms, which have a particular machine as the only one, e.g. a cultivator or a mower. When looking at the column, which includes a mean amount of particular machines, one may notice that a farm is equipped mostly with such machines as: fruit tappers, a fruit stand, a sprayer, a fork lift truck and a tractor.

Fable	1.	Park	macl	hinery	equipment	of	the	researc	hed
group									

<b>NF</b> 1 <b>•</b> • • •	Far	Aver-					
Machines, tools	1	2	3	4	5	6	age
Tractor	2	1	2	2	2	2	1.83
Vehicle	1	1	1	1	1	2	1.17
Plough	1	-	1	1	1	1	0.83
Harrow	1	-	1	1	1	1	0.83
Fertilizer distributor	1	1	1	1	1	1	1.00
Tree planting auger	1	-	-	-	1	1	0.50
Herbicide bar	1	-	1	1	1	1	0.83
Pile driver	1	-	1	1	-	-	0.50
Cultivator	-	-	1	-	-	-	0.17
Soil miller	-	-	1	-	-	1	0.33
Sprayer	3	2	3	3	3	3	2.83
Branch shredder	1	1	-	-	-	-	0.33
Planting rack	6	6	6	6	6	8	6.33
Mower-shredder	-	-	1	1	1	-	0.50
Mower	-	-	-	-	-	1	0.17
Fork lift	2	2	2	3	2	2	2.17
Fruit tappers	10	10	10	8	8	8	9.00
Jumbo boxes trailer	1	-	1	-	-	-	0.33
Electric fork lift truck	-	1	1	1	1	2	1.00
Diesel fork lift truck	1	1	-	-	-	-	0.33
Jumbo boxes leaning machine	1	1	1	1	1	1	1.00
Electronic scale	2	2	-	2	2	2	1.67

Source: author's own study

Particular farms have a similar number of machines and tools. Differences occurring between farms in a quantity of machines they posses are slight and result from low diversity in work technologies. Farm no. 6 has the most numerous machinery park with a total number of machines and tool -37, the second comes farm no. 1 with 36 units.

The farms united in a group are frequently equipped in an old and worn out machinery park (Table 2). It is not a favourable index, since it leads to the increase of the costs incurred on repairs and renovations.

M L	Farm [years]						Aver-
Machines	1	1 2 3 4		4	5	6	age
Tractors- average	16	8	27,5	20	28	18	19.60
Vehicles	4	4	7	11	12	11	7.00
Sprayers	4	8	4	31	31	7	14.17
Fertilizer distributors	6	4	4	7	12	4	6.17
Mowers	-	-	4	30	29	7	11.67

 Table 2. Age of a machinery park (of the selected machines)

[Source: author's own study]

Tractors are the most worn out machines - their average age is 19.5 years. Farm no. 2 is an exception as it has an 8-years old tractor. Fertilizer sprayers with an average age of 6 years were among "the youngest" machines. For farm no. 5, the age is two times higher for the whole population of the researched facilities.

An average installed capacity of tractors amounts to 77.90 kW, whereas in the case of vehicles it is on the level of 87.50 kW. An average installed capacity on 1 ha of AL is 17.47 kW (Table 3). However, it should be noticed that capacity installation is considerably varied - it is between 12.51 kW·ha<sup>-1</sup>AL in the farm no. 5 up to 32.63 in the facility no.6.

Table 3. Install	ed capacity	in the mac	hinery parl	K
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Ma-	Farm	Aver-					
chines	1	2	3	4	5	6	age
Tractors [kW]	88.4	81.0	60.6	88.4	60,6	88.4	77.90
Vehicles [kW]	77.0	77.0	77.0	77.0	77.0	140.0	87.50
Total [kW]	165.4	158.0	137.6	165.4	137.6	228.4	168.90
Average [kW·ha <sup>-1</sup> AL]	23.30	13.74	13.10	16.54	12.51	32.63	17.47

[Source: author's own study]

Table 4 presents a cold storage and storage equipment in the researched farms. All farms, except for the first one, have both first and the second storage facility. Farms no. 3 and 5 (of 100 t load capacity) have the smallest cold storages, whereas the farm no. 2 of 210 t load capacity has the biggest cold storage. A cold storage in farm no. 1 has a slightly lower load capacity (200 t). In the case of storages, the smallest is located in farm no. 6 (60 t), whereas the biggest in farm no. 4 (100 t).

Table	4.	Cold	storage	and	storage	equipment	in the
research	ed :	farms					

Farm	Cold storage (load capacity [t])	Storage (load capacity [t])
1	200	-
2	210	70
3	100	80
4	150	100
5	100	90
6	140	60

[Source: author's own study]

When comparing a storage volume in the researched farms with the production size (Table 1), one may notice that not all of them have a sufficient storage base, shortages occur in the facilities no. 3 and 5.

Presently, the group of producers does not have a full possibility of storing, sorting and packing fruit according to the market expectations. A product is stored in storages and "regular" cold storages and fruit are sorted manually in farms by their members. Such a situation results in non-homogeneous products of low quality, which the group offers. Upon finalization of the 5-year acceptance plan (2010-2014) this situation will be changed due to realisation of the planned technical investments.

<u>Construction of an outbuilding – a storage of agricultural products "fruit" with a socio-technical base</u> and a purchase of a sorting machine and the remaining facilities will allow preparation of fruit for trade in a way expected by recipients. Fruit collected from all members stored in ULO conditions (cold storage with a controlled atmosphere - storing in low-oxygen conditions) and then prepared with large homogeneous parts concerning quality, size and colour, will improve their trading quality and will allow a group to present a better offer. A cold storage constructed by a group will have a total volume of approx. 1300 tons.

<u>A vehicle scale located on a vehicle manoeuvre area</u> <u>will be used to weigh jumbo-boxes and pallets with fruit,</u> trucks and tractors with trailers which supply fruit from the members and at the sale of fruit in large quantities. Lifting capacity of the scale is approx. 60 tons.

The group will purchase two vehicles of varied load capacity. The first vehicle will be of a total mass of approx. 12-15 tons with isotherm and a loading lift of a loading capacity of approx. 5-8 tons. Whereas, the second vehicle will be of a total mass of approx. 5 tons with isotherm and a loading lift of a loading capacity of approx. 2 tons.

<u>TRAFO station construction</u> will be used to supply the building, cold storages and sorting rooms, with a transformer with power indispensable for correct operation of the installed devices.

<u>Purchase of a diesel forklift truck</u> of a lifting capacity of approx. 2500 kg and the height of lifting of approx. 4.5-5.5 m.

<u>Purchase of an electric front three-wheels forklift</u> <u>truck</u> of a lifting capacity of approx. 1600-2000 kg and the height of lifting of approx. 4.5-5.5 m.

<u>Purchase of a forklift truck with a platform for an</u> operator

<u>Purchase of hand pallet trucks</u> in the amount of 6 units of a lifting capacity of approx. 2-2.5 tons each.

<u>Purchase of jumbo boxes</u>, which will be used to store fruit.

<u>Purchase of an orchard platform</u> used to collect fruit in the amount of 6 units. Each orchard platform connected to a farm tractor will carry the maximum of four jumbo boxes.

<u>Purchase of an electronic line for fruit sorting</u>- capacity of a sorting facility is approx.t·h<sup>-1</sup>. The line for sorting apples, including parameters of sorting, inter alia, colour, weight, optic seize. The line for plastic and wooden jumbo boxes, equipped with packing tables. The sorting machine will be equipped with the system of video cameras and software which will enable detection of damages and surface failures on fruit.

Average surface area of the researched farm belonging to the group of producers is 9.67 ha. The whole surface of arable land in all farms was designed for orchards and multi-year plantations. The researched farms are designed for two fruit species: apples and pears. Average surface area of an apple tree plantation is 8.70 ha whereas a pear plantation is 0.97 ha (Figure 1).



[Source: authors' own study] Fig. 1. Surface area of arable lands in the researched farms

An average value of the gross margin obtained from 1 ha of a cultivation, is on the level of 38.96 thousand. PLN·ha<sup>-1</sup>. Whereas an average value of a direct subsidy is 0. 28 thousand PLN·ha<sup>-1</sup>. It results from the obtained data that direct subsidies constitute a small part of the obtained production in relation to the gross margin.



[Source: authors' own study]

**Fig. 2.** The gross margin balance

As much as 99.3% of the value of the obtained production is value of the gross margin, and only 0.7% is direct subsidies (Figure 2). Therefore, it may be concluded that it is a marginal value which almost does not influence efficiency of farms in fruit-growing. While examining the researched facilities regarding the amount of the evaluated index, it is noticed that facility no. 3 manages in the most efficient way (42 thousand PLN·ha<sup>-1</sup>), while facilities no. 1 and 4 are the least efficient (over 36 thousand PLN·ha<sup>-1</sup>).

Farms which belong to the producer group have 10 varieties of apples and 2 varieties of pears in their orchards. Total production potential of all farms is 1550 t of fruit, and apples constitute a considerable majority - 90% of the total fruit production. 232.50 t of apples and 25.83 t of pears are on average in a farm (Table 5).

Table 5. The size of crops in particular farm [t]

Specifi-	Farm	A.v.o.v.o.g.o					
cation	1	2	3	4	5	6	Average
Apples	180	270	270	225	270	180	232.50
Pears	20	30	30	25	30	20	25.83
Total	200	300	300	250	300	200	258.33



[Source: author's own study]

[Source: authors' own study]

Fig. 3. Gross margin and direct subsidies [thousand PLN·t<sup>-1</sup>]

Average value of the gross margin for 1 tone of collected fruit is 1.45 thousand PLN·t<sup>-1</sup>whereas average value of direct subsidies is only 0.01 thousand PLN·t<sup>-1</sup> (figure 3).

#### SUMMARY

The work presents the analysis of farm equipment united in the producer group in the machinery park and its planned modernisation. Quantity equipment of the machinery park and selection of particular machines was pursuant to the production aim. At the same time it allows performance of indispensable agro-technical operations and ensures their realisation on time. Regarding a small scale of production of particular farms, their unification in the group of farm producers increased their chances of access to modern, high-efficient machinery park and a chance for development of their farms. The most important intended investments, that is construction of a cold storage and purchase of electronic line for fruit sorting will ensure new contractors for a group and will strengthen a position of a group on the national and world market due to the supply of considerable uniform production batches. Specificity of the producer group, consisting in the fact that particular members act as individual farmers whereas in other, as an organised group causes that technical production means must be discussed in two aspects. On one hand, it will be a property of particular farmers, on the other a property of a producer group - designed for common use. Additionally, such organisation of the production system does not exclude delivering a service with own machines, both inside the group as well as for non-united farmers. A farmer who is a group member may modernize his own machinery park and at the same time may use expensive and complicated machines and devices purchased commonly, since the purchase of machines and devices is beyond financial abilities of single farmers. Moreover, common use of expensive equipment, highly efficient equipment gives an opportunity to considerably lower unit production costs.

Mean value of the gross margin index, which was obtained for the whole group on the level of 38.96 thousand PLN·ha<sup>-1</sup>AL, allows for the conclusion that orchard production in the researched farms is highly economically effective. Therefore, despite unfavourable agricultural structure (average surface area 9.67 AL) it allows to obtain incomes on the level decisively exceeding income parity.

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# POTENCJAŁ PRODUKCYJNY I TECHNICZNY GOSPODARSTW ZJEDNOCZONYCH W WYBRANEJ GRUPIE PRODUCENTÓW

**Streszczenie.** Celem niniejszej pracy było przeprowadzenie analizy wielkości produkcji i bezpośrednich nakładów związanych z nią, zgodnie z indeksem bilansowym brutto marży, której średnia wartość wyniosła 38,96 tysięcy zł · ha-1AL. Ponadto, opisano urządzenia z bazy technicznej producenta grupy, które ma na celu produkcję owoców. Uzyskane wyniki pozwalają na wniosek, że w przypadku badanych gospodarstw, brak istotnych różnic w ilości urządzeń parku maszynowego, która jest dobrana w zależności od prowadzonej produkcji rolnej. Planowane inwestycje techniczne wykonywane w ramach planu grupy zakładają zakup maszyn i urządzeń, które poprawiają jakość produkcji. W przypadku badanej grupy, najbardziej znaczącą inwestycją jest budowa chłodni z 1300 ton nośności i zakup elektronicznej linii do sortowania owoców o wydajności 4 t  $\cdot$  ha<sup>-1</sup>.

Słowa kluczowe: produkcja rolnicza, park maszynowy, gospodarstwo rolne, grupy producentów.

# Effect of fried dishes assortment on chosen properties of post-frying soybean oils as raw material for production of engine biofuels

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S ummary. The aim of the study was evaluation of effect of fried dishes assortment on quality of obtained postfrying soybean oil, with regard to its utilization as a substrate for production of engine biofuel. For the purpose of analysis of peroxide number, acid number and fatty acids composition, samples of oil after each of five heating cycles from each of three batches of oil differentiated by method of processing preceding oil sampling (frying potato chips, frying breadcrumbs coated fish fingers and heating without fried product) were taken. Purchased soybean oil and post-frying oil prepared during processing of each of above mentioned batches were subjected to esterification with methanol. Fuel obtained this way was used in engine tests.

Heating of soybean oil caused changes in the values of peroxide and acid number and fatty acid composition. These changes were depended on the method of heating oil. Utilization of esters as biocomponent of diesel fuel did not cause significant changes of investigated engine work parameters, when compared to conventional fuel. However, reduction of torque value, decrease of power and increase of specific and hourly fuel consumption were noticeable.

Key words: soybean oil, biodiesel, acid number (AN), peroxide number (PN), fatty acids composition, process of frying.

# INTRODUCTION

Biofuel production of oils and fats is lately an important, principal directions of scientific research [23; 3]. An issue of special importance is a problem developing of post-frying oils and fats [20; 9; 22].

Deep-frying, method of food processing used most often in small gastronomy points, is conducted in fairly high temperature of 170–190°C, what favours processes leading to physical and chemical transformations, both in processed food products and frying medium.

Among transformations occurring in oil being frying medium, oxidation, hydrolysis, polymerization, cycliza-

tion and isomerization are considered to be the most common and the most important [18; 11; 1; 2; 4; 6; 8].

Intensity and type of transformations occurring in particular system are often determined by numerous present in it factors, among which [8] list as basic the following ones: conditions of carrying out the process (its duration, temperature and periodicity) and degree of unsaturation of fatty acids in triglycerides of fat. Among factors shaping properties of frying medium also oxygen availability and amount and composition of compounds released from food (e.g. pro and antioxidants and presence of water) are listed [8].

Numerous transformations occurring in frying medium may be side effect of deep-frying. They are often precursors of synthesis of many various compounds of often complex, and not always determined structure. Products of these transformations can be usually classified in one of two categories: volatile compounds (hydrocarbons, fatty acids and carboxylic compounds) or non-volatile (monomers, dimers, polymers and also some aldehydes and ketones, as well as fatty acids characterizing with changed melting point) [18].

Water transferred into frying environment usually originates from fried products or can be a remain of process of maintenance and cleaning of frying equipment. When present in fat, it is a base for multi-directional hydrolytic transformations, contributing this way to increase of acid number (AN). Moreover, presence of water favours heat transport and stabilization of food frying temperature. At the same time, water vapour partly inhibits oxidation transformations of fat by displacing oxygen in it [8].

Loss of water occurring in fried product is often balanced by sorption of frying fat surrounding fried product. It is a dynamic balance determining process of frying, and shaping properties of product. As a result of these two opposing processes (vaporization and sorption of frying medium) fried product is "enriched" with post-frying oil, which content, dependent on type of fried product and parameters of process, ranges significantly reaching even approx. 40% [8].

High capacity of fryers favours formation of layers of oil, which are more distant from fried product and hence contain less oxygen and water vapour. Above mentioned factors favour mainly polymerization and free-radical transformations of unsaturated fatty acids. The most common result of these transformations are numerous, having complex structure, nonpolar thermal polymers. Macroscopic result of this type of reactions is increase of viscosity and darkening as well as increase of melting point of frying medium, what results in change of its state of aggregation. It results with precipitation of dark brown deposits found on walls of a fryer, which can be a reason for many problems related to utilization of such oil [6].

Searching for alternative energy sources has resulted, in recent years, the development of research on new technologies for production of biofuels from various sources. [5, 10]. However, studies on the use of post-frying vegetable oils as a raw material in biofuels production [9, 20, 12] represent an important new direction of economic and ecological management of the onerous waste produced in a small gastronomy.

## THE AIM OF STUDY

Goal of this research was comparison of physicochemical changes taking place in soybean oil subjected to cyclic heating without fried product with changes caused by heating in process of five-time cyclic frying of potato chips or breadcrumbs coated fish fingers.

Aim of the research was evaluation of effect of fried dishes assortment on quality of obtained post-frying soybean oil, with regard to its utilization as a substrate for production of engine biofuel.

#### MATERIALS AND METHODS

In this research soybean oil purchased in a shop was used as frying medium, and for the purpose of this investigation was called raw soybean oil.

**Preparation of Post-frying Soybean Oils.** From total amount of raw oil, sample for laboratory analyses was taken. It was marked as "0". Remaining amount of oil was divided into three batches and poured into separate containers. First part of oil was heated to temperature of 180°C, which has been maintained for 10 min. Oil was left in the container to cool down to room temperature and than sample for laboratory tests was taken. It was marked as "heating I -without fried product". Second batch of oil was also heated to 180°C, and than potato chips, prepared of purchased raw potatoes and cut to the size and shape of frozen potato chips found in trade, were fried. After frying and separating chips, oil was cooled down to room temperature and than sample for research

was taken. It was marked as "heating I - process of chips frying". Third part of oil (batch no. 3) was heated same way as batch no. 1 and no. 2 but in this case, purchased breadcrumbs coated fish fingers were the fried product. After frying and separating breadcrumbs coated fish fingers, oil was cooled down to room temperature and than sample for research was taken. It was marked as "heating I - process of breadcrumbs coated fish fingers frying".

In consecutive stage of the investigation, after 24 hours, remaining 3 batches were heated again and all described above actions were repeated – yielding another laboratory sample marked as heating II. Whole process of heating, cooling and sampling oil fraction was repeated until it yielded samples marked with numbers III, IV and V.

Chemical Analysis. Each of collected samples was subjected to laboratory tests of peroxide number (PN) [14], acid number (AN) [15] and composition of higher fatty acids [6]. Determination of higher fatty acids composition was conducted by means of method based on utilization of gas chromatography. In this method sample of fat is subjected to alkaline hydrolysis in anhydrous environment with utilization of methanol solution of sodium hydroxide, and mixture of sodium soaps of higher fatty acids of investigated oil is obtained. The mixture is than subjected to reaction of esterification with anhydrous solution of hydrogen chloride in methanol, yielding mixture of fatty acids methyl esters. Obtained methyl esters are separated in a chromatographic column and than their participation in a sum of fatty acids is determined [6]. Chromatographic separation was conducted by means of gas chromatograph with nitrogen as carrier gas, packed column (2.5 m with stationary phase PEGA - polyethylene glycol adipate on carrier GAZ-ChROM-Q and flame ionization detector).

*Methyl Esters Preparation.* Samples of soybean oil which remained after laboratory samples had been taken from each of three batches, differentiated by type of initial preparation (frying potato chips, frying bread-crumbs coated fish fingers and heating without fried product) were separately subjected to esterification with methanol. They were obtained by method analogous to one used in investigation of fatty acids composition by means of gas chromatography [6]. Fuel obtained this way was used in engine tests including main engine work parameters.

*Biofuels Mixtures.* Four mixtures were prepared, each containing 90% diesel fuel and 10% addition of higher fatty acids methyl esters obtained in research and marked as:

- M1 esters obtained from purchased fresh soybean oil,
- M2 esters obtained from soybean oil subjected to five-time cyclic heating without addition of fried product,
- M3 -esters obtained from soybean oil, previously used for five-time cyclic frying of potato chips,
- M4 -esters obtained from soybean oil, previously used for five-time cyclic frying of breadcrumbs coated fish fingers.

As reference engine was powered with diesel fuel (DF).

*Engine Tests.* Above mentioned fuel mixtures, were used for powering 2CA90 diesel engine installed on dynamometric stand for purpose of conducting measurements of its energetic work parameters. Test bed comprised of following devices:

- internal combustion diesel engine 2CA90,
- dynamometric stand composed of eddy-current brake AMX210 and control-measurement system AMX201, AMX 211,
- fuel consumption measuring system,
- system measuring engine parameters: exhaust gasses temperature - tsp, engine oil temperature - tol, oil pressure - pol,
- system measuring state of environment: temperature of environment - tot, atmospheric pressure - pa, and air humidity -φ.

Measurements for each of investigated fuels were conducted and obtained results of energetic parameters were elaborated. Data yielded by measurements was used to draw external characteristics of the engine for rotational speed ranging from minimal to nominal. Carried out research included kinematic and dynamic parameters of the engine: torque - Mo, rotational speed - n, time in which set amount of investigated fuel was used -  $\tau$ . Amount of fuel used for purpose of this characteristic was 50 g. Methodology of measurements and methods of measurements and results reduction of power and torque, were in conformity with norms [13; 17].

#### **RESULTS AND DISCUSSIONS**

Chemical analysis. Raw soybean oil characterised with typical properties for edible oils, fulfilling requirements of recommended in Poland Norm [17], with regard to peroxide number (PN), acid number (AN) as well as composition of higher fatty acids.

Heating soybean oil caused significant decrease of its quality. Peroxide number (PN) of heated samples was significantly increased. It must be noted that diverse course and intensity of these changes were observed in case of samples heated without product, samples heated in process of potato chips and breadcrumbs coated fish fingers frying.

Peroxide number of samples heated in process of potato chips frying, for each of five heating cycles, remained at lower level than in samples of oil heated without fried products. Stabilizing effect of potato chips, caused by sorption of oxidation products on their surface or partial absorption of frying fat, might be explanation of such phenomenon. Similar results were obtained in earlier research concerning rapeseed oil [20] and oil heated in process of potato chips frying [20], had similar course stabilizing at approx. 2 mmol/100g and approx. 1.5 mmol/ 100g respectively (with exemption of null samples and first cycle of soybean oil heated without fried product, differed significantly - reaching almost two times higher value of peroxide number (PN) than respective samples heated in process of potato chips frying. While heating sunflower oil in process of potato chips frying caused only slight decrease of its peroxide number (PN) when compared to samples heated without fried product [9]. Frying breadcrumbs coated fish fingers caused initial, after first and second heating cycle, fast increase of peroxide number of soybean oil, what can probably be related to introduction of fat present in fried product, which was followed by stabilization of peroxide number level, analogous to stabilization observed in process of potato chips frying (Figure 1).



**Fig. 1.** Course of peroxide number (PN) changes during subsequent cycles of soybean oil heating

Acid number (AN) of heated oil samples, was higher than AN observed in samples of raw oil. However, heating in process of potato chips frying caused stabilization of acid number value (AN) at similar level (0.02 mg KOH/g) regardless of number of oil heating cycles, while heating without the product caused systematic increase of AN. Similar course of acid number changes of investigated post-frying oils was also observed in analogous research on rapeseed oil [20] and sunflower oil samples [9]. Probable cause of observed changes of acid number of these samples is sorption of oxidation products on surface of, subjected to culinary processing, potato chips, or partial absorption of oil surrounding product into its deeper, more distant from surface of investigated raw product, layers.





Heating soybean oil in process of breles, reaching values lower than in respective samples of soybean oil heated without fried product (Figure 2). Two opposing processes were the most probable cause of above described course of changes of acid number (AN) in samples of soybean oil heated in process of breadcrumbs coated fish fingers frying. Increase of AN should be explained with oxidation of higher fatty acids and hydrolytic effect of water and water vapour, released from product as a result of frying, while stabilization of its level occurred as an effect of sorption of oxidation products in surface layer of fried product.

It should be noted that composition of higher fatty acids of raw soybean oil was  $_{40}$  typical for this product. Properties of this  $_{30}$  oil are determined mainly by three unsa- $_{10}$ turated fatty acids (linolenic, oleic and li- $_{0}$  noleic), proportion of content of which in raw oil is 1:4.3:8.8 (Figure 3). B o t h , heating without fried product as well as process of breadcrumbs coated fish finficant changes of soybean oil properties. These changes are mainly result of significant decrease of oil higher fatty acids content and significant increase of oxidation products content (Figure 3-5), what was confirmed by earlier research on this problem conducted on samples of rapeseed [20] and sunflower oil [9].

Frying breadcrumbs coated fish fingers or potato chips caused partial stabilization of higher fatty acids composition, what can be noted in case of two, dominating in soybean, fatty acids i.e. oleic and linoleic. Their content in typical raw soybean oil often exceeds 75% (Figure 3-5), [19; 21]. Five-time cyclic heating of soybean oil only slightly changed proportion of oleic to linoleic acid, for in raw oil, on one particle of oleic acid statistically slightly more than two particles of linoleic acid are found. After process of heating, this rate is approx. 1:1.5, from 1:1.4 for sample heated without fried product, through 1:1,50 for sample heated in the process of frying potato chips, and up to 1:1.63 when sample of oil heated in the process of frying breadcrumbs coated fish fingers was investigated.

The same processes of heating caused also slight changes of saturated fatty acids ratio. In fresh soybean oil, on one particle of stearic acid 2.66 particles of palmitic acid are found, while after five cycles of heating this ratio was from 1:2.1 in oil heated without product (Figure 3), through 1:2.31 in oil subjected to heating in process of potato chips frying (Figure 5) to 1:2.38 in oil subjected to heating in process of breadcrumbs coated fish fingers frying (Figure 4).



**Fig. 3.** Composition of higher fatty acids of soybean oil subjected to five-time cyclic heating without fried product AN for first two cycles of heating remained at level siver, starting from the third heating cycle <sup>90</sup> AN exceeded this value and was systema-<sup>80</sup>



**Fig. 4.** Composition of higher fatty acids of soybean oil subjected to five-time cyclic heating in process of breadcrumbs coated fish fingers frying



**Fig. 5.** Composition of higher fatty acids of soybean oil subjected to fivegers or potato chips frying caused signi-time cyclic heating in process of potato chips frying

Cyclic five-time heating of soybean oil contributed to occurrence of clear change i.e. increase of linolenic acid content in proportion to unsaturated fatty acids. After five cycles of heating, on one particle of linolenic acid from 2.34 to 2.69 particles of oleic acid, and from 3.50 to 4.14 particles of linoleic acid were found (Figure 3, 4, 5), while in raw oil respective values were 4.3 and 8.8.

Utilization of post-frying soybean oil for production of components of higher fatty acids esters as engine biofuels seems to be hindered mainly by elevated acidity of raw material and significant content of oxidation products of higher fatty acids, which could not be identified by means of chromatography. However, up to date research on utilization of post-frying rapeseed oil has not confirmed these doubts [12].

In conclusions, being summary of this research, authors indicate fact that elevated acidity of post-frying oils is neutralized during stage of alkaline hydrolysis, which is an essential phase of transforming oil into fatty acids methyl esters. Unidentified oxidation products undergo similar transformations in the process of fatty acids methyl esters formation, and are not a significant obstacle in correct operation of diesel engines powered with such type of biofuel [12]. Stabilizing effect of fried product, e.g. potato chips [20], on proportion of higher fatty acids of post-frying oil is also emphasized.

*Engine Tests.* Presented current engine tests seem to confirm previously observed patterns [12]. Utilization of mixtures of diesel fuel and 10% addition of fatty acids methyl esters derived from purchased raw soybean oil and

post-frying oils, obtained after five-time cyclic heating without fried product and after five-time cyclic frying of potato chips or breadcrumbs coated fish fingers, lead to decrease of power of engine powered with these mixtures, when compared to conventional diesel fuel (Figure 6). Similarly as in previously mentioned research [12], course of curves of engine power in relation to its rotational speed showed similar course and character. Differences in course of changes of these curves (Figure 6) for above mentioned mixtures containing 10% addition of esters, are similar and all of them have similar effect on changes of power of investigated engine in relation to its these changes course, regardless of utilized fuel mixtures rotational speed. (Figure 7). These results are also confirmed by prior research [12].



**Fig. 6.** Course of power changes of 2CA90 engine powered with diesel fuel and mixtures of fatty acids methyl esters and diesel fuel: a) M1 - esters obtained from purchased fresh soybean oil, b) M2 - esters obtained from soybean oil subjected to five-time cyclic heating without addition of fried product, c) M3 -esters obtained from soybean oil, previously used for five-time cyclic frying of potato chips, d) M4 - esters obtained from soybean oil, previously used for five-time cyclic frying of breadcrumbs coated fish fingers, e) DF - diesel fuel



**Fig. 7.** Course of torque changes of 2CA90 engine powered with diesel fuel and mixtures of fatty acids methyl esters and diesel fuel: a) M1 - esters obtained from purchased fresh soybean oil, b) M2 - esters obtained from soybean oil subjected to five-time cyclic heating without addition of fried product, c) M3 -esters obtained from soybean oil, previously used for five-time cyclic frying of potato chips d) M4 - esters obtained from soybean oil, previously used for five-time cyclic frying of breadcrumbs coated fish fingers, e) DF - diesel fuel

Approximation of research data, including investigation of course of 2CA90 engine torque changes in relasts on 2CA90 engine, demonstrate significantly lower consumption of fuel when conventional diesel fuel is used. Curves of fuel consumption for investigated fuel mixtures, when compared with results for DF, characterize with higher values at each of investigated rotational speeds. At the same time they all have similar character and considerable similarity of course. It suggests insignificance of differences between them. Similar results were obtained in previous research [12].



**Fig. 8.** Course of specific fuel consumption changes of 2CA90 engine powered with diesel fuel and mixtures of fatty acids methyl esters and diesel fuel: a) M1 -esters obtained from purchased fresh soybean oil, b) M2 - esters obtained from soybean oil subjected to five-time cyclic heating without addition of fried product, c) M3 - esters obtained from soybean oil, previously used for five-time cyclic frying of potato chips d) M4 - esters obtained from soybean oil, previously used for five-time cyclic frying of breadcrumbs coated fish fingers, e) DF - diesel fuel

# CONCLUSIONS

Relying on results of carried out investigation following conclusions can be formulated:

- 1. Cyclic, model heating of soybean oil, and especially three first cycles, contribute to significant changes in composition of higher fatty acids. It results with decrease of unsaturated fatty acids content, significant increase of oxidation products content and changes of peroxide number (PN) and acid number (AN) of heated oil.
- 2. Heating soybean oil in process of frying products like breadcrumbs coated fish fingers or potato chips affects stabilization of amount of peroxide products present in post-frying oil, what leads to decrease of peroxide number (PN) of such oil in comparison to process of heating without fried products.
- 3. Acid number (AN) of post-frying soybean oil obtained after frying potato chips stabilizes, while frying breadcrumbs coated fish fingers and heating oil without fried product contribute to gradual increase of AN.
- 4. Frying breadcrumbs coated fish fingers and potato chips favour stabilisation of proportion of oleic and

linolic acid in investigated post-frying oil, at level similar to one noted in case of purchased raw soybean oil.

5. Unification of properties of post-frying soybean oil occurring during stage of chemical conversion to fatty acids methyl esters, contributes to unification of properties of biofuels prepared on base of various batches of post-frying oil and favours utilization of post-frying oils which proved as suitable for production of biofuel components as fresh soybean oil.



**Fig. 9.** Hourly fuel consumption of 2CA90 engine powered with diesel fuel and mixtures of fatty acids methyl esters and diesel fuel: a) M1 - esters obtained from purchased fresh soybean oil, b) M2 - esters obtained from soybean oil subjected to five-time cyclic heating without addition of fried product, c) M3 -esters obtained from soybean oil, previously used for five-time cyclic frying of potato chips d) M4 - esters obtained from soybean oil, previously used for breadcrumbs coated fish fingers, e) DF - diesel fuel

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## EFFECT OF FRIED DISHES ASSORTMENT ON CHOSEN PRO-PERTIES OF POST-FRYING SOYBEAN OILS AS RAW MATERIAL FOR PRODUCTION OF ENGINE BIOFUELS [**PO POLSKU**]

Streszczenie. Celem pracy była ocena wpływu asortymentu dań smażonych na jakość otrzymanego po smażeniu oleju sojowego, w odniesieniu do jego wykorzystania jako bazy dla produkcji biopaliwa do silników. Dla celów analizy liczby nadtlenkowej, ilości kwasów i kwasów tłuszczowych, pobrano próbki oleju po każdym z pięciu cyklów ogrzewania z każdego z trzech partii oleju zróżnicowanego w zależności od metody przetwarzania (po smażeniu frytek, paluszków rybnych powlekanych bułką tartą i po ogrzewaniu bez smażonego produktu). Zakupiony olej sojowy oraz olej po smażeniu podczas przetwarzania każdej z wyżej wymienionych partii poddano estryfikacji metanolem. Paliwo uzyskane w ten sposób było używane w testach silnikowych. Ogrzewanie oleju sojowego powodowało zmiany wartości liczby nadtlenkowej i kwasowej i składu kwasów tłuszczowych. Zmiany te były uzależnione od sposobu ogrzewania oleju.

Wykorzystanie estrów jako biokomponentu oleju napędowego nie spowodowało istotnych zmian parametrów pracy badanego silnika, w porównaniu z konwencjonalnym paliwem. Jednakże zauważono obniżenie wartości momentu obrotowego, zmniejszenie mocy i wzrost całkowitego oraz godzinowego zużycia paliwa.

Słowa kluczowe: olej sojowy, biodiesel, liczba kwasowa (AN), liczba nadtlenkowa (PN), skład kwasów tłuszczowych, proces smażenia.

# Efficiency of the generating set with synchronous generator supplied with single-phase electricity receivers

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Summary. The paper presents the analysis of efficiency changes of synchronous generating set supplying the singlephase receiver sets. The laboratory stand was described as well as the methodology of investigations. On the basis of investigation results, the influence was evaluated of size and character of electricity receiver on the efficiency of generating set.

Key words: synchronous generating set, efficiency of generating set.

#### INTRODUCTION

Electrical equipment applied on the farm is used continuously, cyclically, or incidentally. An example of continuous operation is to maintain a specific climate in livestock buildings (ventilation, heating, humidification, etc.). Cycler work concerns the room operations, preparation of feed or handling animals (milking cows, feeding the feed, milk cooling, etc.). In these cases, the correct work requires continuity of electricity supply. Its primary source is a professional power network. In the case of individual consumers, it does not have the possibility of bilateral supplying. This forces the use of the reserve source of electrical energy. The source of the reserve in relation to controls, which is unacceptable for even a momentary loss of power are usually UPS. On the other hand, a typical device requires sources with higher power and a sufficiently long time of power reserve, such as generating sets.

Typical electrical appliances on the farm are refrigerators, motors, 1-phase heaters and lighting. In this case allowable power interruption time varies from several minutes to about 1 hour. Thus, a sufficient source of backup in a typical farm may be one-phase generating set with manual start-up [6].

# SYNCHRONOUS GENERATING SET

The generating set consists of two main components: the drive and generator (Fig. 1). Propelling device is usually an internal combustion engine with spark ignition. The power is transferred to an electric generator synchronous or asynchronous. Here, mechanical energy is converted into electrical energy.



Fig. 1. Layout of generating set

The quality of parameters of energy (230V and 50 Hz) is achieved by maintaining the speed and the selection of the magnetizing current. So, the device additionally includes the system of speed control and field current regulator.

A typical synchronous generator consists of two main parts [5, 9, 15]: the stator (armature) and rotor, which is the magnetizer (Fig. 2).



Fig. 2. The schematic diagram of the synchronous machine [15]

The flow of direct current through the magnetizing winding wound on the rotor of the generator produces a magnetic flux. The stream is rotated with the rotor windings, at the same speed relative to the stator induces in its winding an AC voltage. The value of this voltage affects magnetizing current. The frequency of the generating voltage is directly proportional to the rotor speed.

The conversion of mechanical energy to electrical energy occurs with certain efficiency. It shall be changed with the changes of power and the type of connected electricity receivers. Hence the aim of the described study was to determine the efficiency of energy conversion depending on the generator load.

#### LABORATORY STAND

Measurements were conducted on the laboratory stand (Fig. 3) made in the Department of Technology Fundamentals at the University of Life Sciences in Lublin. The investigations were carried out on the single-phase synchronous generator (1) the type EA 2000 about the nominal power  $P_n = 1,7$  kW, the indicative power  $S_n = 2$  kVA, the nominal voltage  $U_n = 230$  V and the nominal intensity of current  $I_n = 8,7$  A.



**Fig. 3.** The laboratory stand to measure the efficiency of power generating set: 1. power generating set, 2. fuel measurement system, 3. inductive load, 4. resistive load, 5. energy power meter

The engine of generating set (1) has a modified fuel system. The carburetor unit is supplied via calibrated burette (2). This allows for measuring doses of burned fuel. The time to obtain a specified portion of the burned fuel was measured using a stopwatch. The inductive elements (3) and a resistance (4) were used to load the generator. Measurement of the load power was provided by multi-parameter energy power meter (5).

#### METHODOLOGY

The generator is followed by conversion of mechanical energy into electrical energy. The mechanical energy produced in the combustion engine is the result of thermal energy  $Q_p$  generating from the combustion of fuel. The end result is generating electricity  $(W_p)$ .

To determine the efficiency of processing, a specified amount of thermal energy  $(Q_p)$  was obtained after combustion of fuel metered dose (V) and the amount of power  $(W_p)$  produced by the generator. Thermal energy is based on the volume of spent fuel and its calorific value  $(c_{x})$ :

$$Q_{\rm p} = V * c_{\rm p}, [J]. \tag{1}$$

The amount of electricity  $(W_p)$  is based on the measured electrical power (P) received from the generator and the combustion time  $(t_p)$  at a certain amount of fuel (V):

$$W_{\rm p} = P * t_{\rm s}, \, [J].$$
 (2)

The energy conversion efficiency is based on the formula:

$$\eta = W_{\rm p} / Q_{\rm p}. \tag{3}$$

# THE RESULTS OF INVESTIGATION

During the study unleaded petrol Pb95 was used. The calorific value is dependent on the manufacturer and distributor of fuel and is between 29-38 MJ/ m<sup>3</sup> [11, 12, 13, 14]. For the calculation purposes the calorific value was equal to 32 MJ/m<sup>3</sup>. During each measurement 5 cm<sup>3</sup> of fuel was consumed.

In the first part of the study the generator was debited by resistance. The load varied from no load to 1,07 of generator rated power. The results are summarized in Table 1.

**Table 1.** The investigation results of the synchronous generating set load resistance

<i>P</i> , W	t <sub>s</sub> , s	W <sub>p</sub> , J	$Q_{\rm p}, { m J}$	η, -
0	32,6	0	160000	0,000
208	30,1	6268	160000	0,039
423	28,1	11877	160000	0,074
605	26,4	15992	160000	0,100
878	22,5	19792	160000	0,124
1120	19,7	22027	160000	0,138
1418	17,6	24957	160000	0,156
1668	15,6	26021	160000	0,163
1760	14,6	25701	160000	0,161

Then, resistive-inductive load was attached to the generator. Constant active power was kept of about 1 kW and 0,5 kW and varied inductive load. The measurement results are shown in Table 2 and Table 3.

**Table 2.** The investigation results of the synchronous generator with resistive-inductive load for  $P \approx 1 \text{kW}$ 

cos <i>φ</i> , -	<i>t</i> <sub>s</sub> , s	W <sub>p</sub> , J	$Q_{\rm p},{ m J}$	η, -
0,59	21,0	12629	190000	0,066
0,80	17,0	17114	190000	0,090
1,00	20,4	21711	190000	0,114

cos <i>φ</i> , -	t <sub>s</sub> , s	W <sub>p</sub> , J	$Q_{\rm p},{ m J}$	η, -
0,50	22,2	11645	190000	0,061
0,55	25,7	13604	190000	0,072
0,65	26,2	14358	190000	0,076
0,85	28,7	15737	190000	0,083
1,00	27,9	14814	190000	0,078

**Table 3.** The investigation results of the synchronous generator with resistive-inductive load for  $P \approx 0.5 \text{kW}$ 

# THE ANALYSIS OF INVESTIGATION RESULTS

The analysis results are presented as graphs of changes efficiency  $\eta$  as a function of load power changes *P* or changes of the power factor  $\cos\phi$ .



**Fig. 4.** The graph of changes of the efficiency of the generating set when changing the load power

Figure 4 shows the change in the efficiency of the generating set as a function of power factor, for constant loading generator active power equal to 1 kW. Increasing the generator load increases the efficiency of energy conversion. The maximum efficiency of 16,3% was achieved for the power of 1,67 kW load. The energy conversion efficiency increases linearly from 0 to 10% power in range from 0 to about 0,6 kW. Further increase in power up to 1,67 kW is an approximately linear increase in efficiency to 16,3%. In this range, efficiency gains are smaller than before. Exceeding the rated power causes a decrease in efficiency. At 1,76 kW load power efficiency is 16,1%.

The course of changes in the efficiency of the generating set as a function of load power is of a different nature than changes of the electrical efficiency of the generator itself. In a typical generator, the efficiency initially increases rapidly, and in a wide range of loadings it remains practically constant [2, 4]. The efficiency of the generator is dominated here by the internal combustion engine efficiency as a function of load torque. Changes of the internal combustion engine efficiency initially increases slightly as a function of load torque and then, after reaching the maximum, it slightly decreases [1, 7].



Fig. 5. The graph of changes of the efficiency of the generating set when changing the power factor for load  $P \approx 1 \text{ kW}$ 

Figure 5 shows the change in the efficiency of the generating set as a function of power factor for the constant active power loading generator equal to 1 kW.

In this case, the efficiency increases with increasing generator power factor. When the active power load is 1kW, the increase of power factor  $cos\phi$  from 0,6 to 1,0 increases the efficiency of the generator from 6,6% to 11,4%.

Changes in the efficiency of the generator as a function of the power factor for a constant active power loading generator of 0,5 kW are shown in Figure 6.



**Fig. 6.** The graph of changes of the efficiency of the generating set when changing the power factor for load  $P \approx 0.5$  kW

When the active power load is 0,5 kW, the increase of power factor  $cos\phi$  from 0,5 to 1,0 increases the efficiency of the generator from 6,1% to 8,3%.

Increase of the power factor is associated with the reduction in the reactive current of supply receiver. This reduces energy loss and thus increases efficiency.

#### CONCLUSIONS

The study showed that the efficiency of single-phase synchronous generating set of low power is small. The maximum one was 16.1%. The highest value of efficiency is achieved at the load with an output power close to the rated power of generator.

So, from the economic point of view, the power of the generator must be matched to the power supplied by loads, so that it worked with the power unit similar to the plate. However, this implies an increased emission of pollutants into the environment [3, 8, 10].

The most efficient use of energy contained in the fuel is possible with supplying resistive loads, such as incandescent lighting or convection heating.

The supply of resistive-inductive (RL) devices causes a decrease in the efficiency of the electric generating set. Thus, it may be expedient to use systems for reactive power compensation.

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# SPRAWNOŚĆ ZESPOŁU PRĄDOTWÓRCZEGO Z SYNCHRONICZNYM GENERATOREM WYPOSAŻONYM W JEDNOFAZOWE Z ODBIORNIKI ELEKTRYCZNE

Streszczenie. W artykule przedstawiono analizę zmian sprawności zespołu prądotwórczego z generatorem synchronicznym zasilającego odbiorniki jednofazowe. Opisano stanowisko badawcze i metodykę badań. Na podstawie przeprowadzonych pomiarów dokonano oceny wpływu wielkości i charakteru obciążenia na sprawność pracy zespołu prądotwórczego.

Słowa kluczowe: zespół prądotwórczy, sprawność zespołu prądotwórczego.

# Modelling of the diesel engine in researches of dynamics of machine tractor units

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Summary. The article presents the mathematical description of diesel engines of machine tractor units of different function in researches of their dynamics stated by working out of new technics. It considers the methodical positions of modelling of diesel engines in various problems of dynamics of tractor units. The developed variants of mathematical descriptions of the diesel engine are presented, and the variant choice is defined by problems of concrete research of dynamics of the machine tractor unit.

Key words: machine tractor unit, modelling dynamics, mathematical description of the diesel engine, dynamics research.

#### **INTRODUCTION**

Perfection of machine tractor units (MTU) has led to an essential intensification of their working processes, increase of individual capacities, frequently, speeds of movement, load-carrying capacity or tonnage, the main technological parameters, for example, width of capture, and also to a combination of technological process by combination within the limits of one unit of several technological operations, for example, pre-seeding processing of soil, etc. [2, 7, 8, 18, 19, 20, 21]. However all it also has resulted and to high dynamism of such tractor units. Has caused application of the branched out mechanical and hydro-mechanical drives wheels, active working bodies and made active driving wheels on the technological module aggregated with a tractor, essential change of their constructive concept, use of diesel engines with more progressive systems of giving of fuel, wide application of electronics in automatic control systems high-speed and power modes of such diesel engines. The listed changes demand the further consideration [2, 5, 7, 9, 13, 17], for the purpose of development of the theory of perspective tractor units for the proved choice of rational constructive and regime parameters, both the unit as a whole, and its functional subsystems, for example, the engine,

a transmission, communications between bridges and communications between transmission wheels, etc.

Creation of tractor technological units on the basis of a wheel tractor with inevitability leads to necessity of the account of dynamic loadings for transmission. It is essential, as engine parameters, inertial and geometrical parameters of the unit, rigidity, a friction and energy dispersion, rotating weights in transmission cause character and levels of fluctuations of moving weights and loadings. Such loadings can surpass many times over static, and therefore they are necessary for knowing correctly to choose settlement values at durability and resource calculations of the projected unit, and also for a correct estimation of a spectrum of defining operational properties of the created machine tractor unit.

In the article the methodical positions of modelling of diesel engines in various problems of dynamics of tractor units are considered.

# THE MATHEMATICAL DESCRIPTION OF THE DIESEL ENGINE AT THE DECISION OF PROBLEMS OF DYNAMICS OF MACHINE TRACTOR UNITS

At designing of self-propelled cars it is necessary to model the characteristic of the diesel engine, that, frequently, at a stage of predesign researches, represents some difficulty. We will consider an order of construction of such characteristic on a concrete example of an atmospheric diesel engine with multiphase a regulator of all modes.

- Let us accept the following data, for example:
- demanded rated power engine,  $P_{e_{nom}} = 58,5$  [kW];
- nominal frequency of rotation of cranked shaft of the engine,  $n_{nom} = 2100$  [rpm];
- specific expense of fuel on a nominal mode,  $g_e = 222$ [g·(kW·h)<sup>-1</sup>].

Calculations are carried out in the following sequence. The nominal torque of the engine:

$$M_{e_{nom}} = \frac{60P_{e_{nom}}}{2\pi \cdot n_{nom}} = \frac{P_{e_{nom}}}{\omega_{nom}} [\text{kN·m}];$$
$$M_{e_{nom}} = \frac{60 \cdot 58.5 \cdot 1000}{2 \cdot 3.14 \cdot 2100} = 266.2 [\text{N·m}].$$

Accepting the factor of torque set  $\mu = 15\%$  that is characteristic for atmospheric diesel engines, we find the maximum torque of the engine:

$$M_{\max} = \frac{100 + \mu}{100} \cdot M_{e_{nom}} = \frac{100 + 15}{100} \cdot 266.2 = 306[\text{N} \cdot \text{m}]$$

Factor adaptations on the torque :

$$\chi_P = \frac{M_{\text{max}}}{M_{e_{\text{max}}}} = \frac{306}{266.2} = 1.15$$

Accepting degree of non-uniformity of a regulator of the tractor engine -  $\delta = 6\%$ , we define the maximum frequency of rotation of a cranked shaft of the engine:

$$n_{\text{max}} = n_{\text{nom}} \cdot \frac{200 + \delta}{200 - \delta} = 2100 \cdot \frac{200 + 6}{200 - 6} \approx 2300 \text{[rpm]}.$$

Let us accept factor adaptations on frequency as

$$\chi_B = \frac{n_{nom}}{n_{\min}} = 1.45.$$

where:  $n_{\min}$  - the minimum frequency of steady work of the engine, often accepted at  $n_{\min} = n_{M_{\max}}$ .

Then values of factors [5] are equal to, in Lejder- (man's S.R. formulas:

$$a = \frac{\chi_{P} \cdot \chi_{B} \cdot (2 - \chi_{B}) - 1}{\chi_{B} \cdot (2 - \chi_{B}) - 1}, a=0,41;$$
  

$$b = -\frac{2 \cdot \chi_{B} \cdot (\chi_{P} - 1)}{\chi_{B} \cdot (2 - \chi_{B}) - 1}, b=2,15;$$
  

$$c = \frac{\chi_{B}^{2} \cdot (\chi_{P} - 1)}{\chi_{B} \cdot (2 - \chi_{B}) - 1}, \text{ with } =-1,56.$$

As check converges: a+b+c = 1 factors of the formula of Lejderman's S.R. are defined correctly. Then capacity of the engine at a preset value of frequency of rotation of a cranked shaft is defined from the expression:

$$P_e = P_{e_{nom}} \times \left[ a \cdot \frac{n}{n_{\max}} + b \cdot \left(\frac{n}{n_{\max}}\right)^2 - c \cdot \left(\frac{n}{n_{\max}}\right)^3 \right]$$

Using the calculated values of capacity of the engine, we calculate values of the current torque of the engine under the formula:

$$M_e = \frac{60P_e}{2\pi \cdot n}.$$

The hourly expense of fuel at rated power [1]:

$$G_{h_{nom}} = g_{e_{nom}} \cdot P_{e_{nom}} / 1000 = 222 \cdot 58.5 / 1000 = 13 [kg \cdot h^{-1}].$$

We count the hour expense of fuel at the maximum frequency of rotation of a cranked shaft, accepting average for diesel engines of concrete type factor of communication of hourly expenses of fuel of a diesel engine with all regulator modes at rated power and at the maximum turns of the idling, equal k=0,25, then:

$$G_{h_x} = k \cdot G_{h_{nom}} = 0.25 \cdot 13 = 3.25 [\text{kg·h}^{-1}]$$

If an argument accepts torque frequency of rotation of a cranked shaft of the engine, hourly and specific effective fuel expenses, at change of the torque from zero to rating value (for a working branch of a regulator), it is possible to define branches of the high-speed characteristic of the engine under formulas:

$$n = n_{\max} - (n_{\max} - n_{nom}) \frac{M_e}{M_{e_{nom}}}, \ G_h = (G_{h_{nom}} - G_{h_x}) \frac{M_e n}{M_{e_{nom}} n_{nom}},$$
$$g_h = (g_{h_{nom}} - g_{h_x}) \cdot \frac{M_e \cdot n}{M_{e_{nom}} \cdot n_{nom}},$$

and at change of the torque from nominal to the maximum value ( for an external branch) can be defined numerical values of the same sizes on expressions:

$$n = n_{nom} \left( \alpha + (1 - \alpha) \sqrt{\frac{M_{e_{max}} - M_{e}}{M_{e_{max}}}} \right),$$

$$G_{h} = G_{h_{nom}} \left[ \frac{\gamma - \alpha^{2}}{1 - \alpha} \left( 1 - \frac{n}{n_{nom}} \right) + \left( \frac{n}{n_{nom}} \right)^{2} \right] \frac{M_{e}n}{M_{e_{nom}} n_{nom}},$$
where:  $\alpha = \frac{1}{\chi_{B}} = \frac{n_{M_{max}}}{n_{nom}}$  - degree of decrease in fre-

quency of rotation of a cranked shaft of the engine in the field of use of a stock of the torque, we accept 0,7;  $\gamma$  - degree of change of the specific expense of fuel on an external branch of the high-speed characteristic, we accept 1,05.

Capacity of the engine and the specific expense on external characteristic branches are counted under formulas:

Let us carry out calculations on the resulted algorithm at various values of the torque on an engine shaft: from a mode of the maximum torque and to an idling mode. By results of calculations it is possible to construct a working branch of a regulator the loading characteristic -  $P_e$  $(M_e)$ ,  $n (M_e)$ ,  $G_b (M_e)$ ,  $g_e (M_e)$  (Fig. 1).

By results of the same calculations it is possible to construct as frequency of rotation of a shaft of the engine the high-speed characteristic of a diesel engine - schedules of dependences  $P_e(n)$ ,  $M_e(n)$ ,  $G_h(n)$ ,  $g_e(n)$  (Fig. 2).

Capacity of the engine and the specific expense on an external branch of the characteristic are counted under formulas:

$$P_{e} = \frac{\pi \cdot n \cdot M_{e}}{30} \text{ M } g_{e} = \frac{1000 \cdot G_{h}}{P_{e}}, \text{ [g} \cdot (\text{kW} \cdot \text{h})^{-1}\text{]}.$$



Fig. 1. Settlement of regulatory characteristic of the diesel engine capacity 58,5 kW



Fig. 2. Settlement of external high-speed characteristic of the diesel engine capacity 58,5 kW

Figures 1 and 2 present characteristics of the diesel engine use at the design static analysis of traction and traction-dynamic properties of a developed tractor or the machine tractor unit [1, 2, 3, 4, 6, 7, 8, 9].

For research of transitive modes of projected tractor units on the developed mathematical models it is also necessary to define the current torque of the engine.

The mathematical model of a tractor diesel engine in this case can be made at an assumption that in transitive modes character of dependence of the moment of the engine from frequency of rotation, positions of a pedal of "gas" and position of the lever of a regulator does not differ essentially from those at equilibrium high-speed modes. Though in the known monograph of academician V.N.Boltinskij "Work of the tractor engine at unsteady loading" data about presence of such influence are cited.

- Considering the diesel engine as adjustable system, it represent two dynamic links:
- The first actually the engine in the form of inertial weight which has as an input angular speed  $\omega$  and a feedback with a regulator of the fuel pump on its course lever of giving of fuel  $h_p$ , and also has an exit twisting moment  $M_z$ ;
- The second all modes a regulator of the fuel pump of a high pressure which has one input - angular speed  $\omega$ , and the second input - lever position  $x_p$  fuel supply whereas an exit is the course lever of giving of fuel  $h_p$ .

From the above it follows, that the torque of the engine is defined as function of two variables in the form of  $M_e = f(\omega, h_p)$ . And though in transitive modes mutual change of arguments of this function leads to instant values of the moment of the engine, differing from static, but, taking into account the accepted assumption, the model of the moment of a diesel engine is accepted not the inertial factorial, describing static high-speed characteristics of the engine at the various fixed positions lever of giving of fuel the fuel pump [7, 8, 10, 11, 12, 15, 20].

As the analytical description of dependence of moment  $M_e$  only from angular speed *n* (Fig. 2), use resulted before expression.

By working out of programs of management by engines, it is useful to use the complex characteristic of the diesel engine (Fig. 3) [14, 16, 18, 20].



Fig. 3. The complex high-speed characteristic of a tractor diesel engine.

Continuous lines in (Fig. 3) it a working branch of a regulator and external branches of the high-speed characteristic of the diesel engine; shaped - auxiliary lines of constant capacity; strokes-dashed lines - isolinescharacteristics of the specific expense of fuel; ab - the characteristic of the minimum specific effective expense of fuel.

Apparently from the analysis of (Fig. 3) resulted expressions do not change and for partial characteristics, only values of parameters  $M_{e_{nom}}, \omega_{nom}, \omega$  for partial characteristics (Fig. 3) are functions of position of the lever  $x_p$  supply of fuel and are easily defined on the basis of the experimental characteristic whose example for diesel without pressuring the engine is resulted in the specified figure. The given characteristic is convenient at development of strategy of engine management which then is pawned in the form of the program in the microprocessor module of automatic control by the engine.

In (Fig. 4) the model of the tractor diesel engine with two inputs is shown. It is necessary at research few the studied transitive modes of tractor units. For example, the processes connected with incorporated joint automatic control engine-transmission-wheels by installation of a tractor with volume hydro-mechanical transfer. In such a system of engine-transmission-wheels simultaneous influences on the lever of giving of fuel, on corners of turn of cradles of hydro-cars volume hydro-mechanical transfer and on structural transfer of wheels take place, for example at automatic connection of the additional leading bridge.



Fig. 4. Model of a tractor diesel engine with all regulator modes

To key parameters of a regulator of the fuel pump, subject to definition as initial data, the following concerns: led at connecting knot weight of moving parts of the fuel pump and a regulator  $m_p$ , inertial factor of cargoes A, factor of an internal friction  $v_p$  and restoring force E of connecting knot a regulator on the core and partial high-speed modes. The factor depends on position z of connecting knot a regulator, i.e. A=f(z); the factor  $v_p$  for modern high-speed diesel engines practically does not depend on relative speed of displacement of rubbing bodies centrifugal of connecting knot a regulator and can be accepted in constant size; force E according to the accepted scheme of model will depend on two sizes and is described by function  $E=f(z, x_p)$  [13, 17, 19, 21, 20].

Static balance of a regulator is defined by equality  $E=A \cdot \omega_p^2$  (here  $\omega_p$  - angular speed of a shaft of a regulator).

In transitive modes the equation of a regulator looks as:

$$m_p \cdot z + v_p \cdot z + E = A \cdot \omega_p^2.$$

In a general view the factorial model of a diesel engine with all modes a regulator is expressed by the modelling expressions offered by Solonskij A.S. and Vernigor V. A:

$$Me = -C_1 - C_2 \cdot \omega + C_3 \cdot h_p + C_4 \cdot \omega^2 - -C_5 \cdot h_p^2 - C_6 \cdot h_p \cdot \omega^2 + C_7 \cdot \omega \cdot h_p^2, \text{ [N·m]},$$

$$m_p \cdot z + v_p \cdot z + E = A \cdot \omega_p^2, h_p = z \cdot \frac{R}{r}; A = C_8 + C_9 \cdot z, [N \cdot s^2 \cdot rad^{-2}].$$
Restoring force E:

on working branches external and partial high-speed characteristics

$$E = E_p = C_{10} - C_{11} \cdot x_p + C_{12} \cdot z - -C_{13} \cdot z \cdot x_p - C_{14} \cdot x_p^2 + C_{15} \cdot z^2, [N],$$

 on external branches of the external high-speed characteristic

$$E = E_p = C_{16} + C_{17} \cdot z$$
, [N].

The hour expense of fuel is defined from expression

$$G_{h} = -C_{18} - C_{19} \cdot \omega + C_{20} \cdot h_{p} + C_{21} \cdot h_{p} \cdot \omega$$
, [kg·h<sup>-1</sup>],

where:  $C_1 \cdot C_{21}$  - constants of modelling expressions which are defined at identification of a tractor diesel engine by a method of adjusted model by results of natural tests of the engine [3, 5, 6, 20].

At moving of the lever of giving of fuel system the engine-regulator works as watching system of automatic control (SAC), and at invariable position of this lever - as automatic regulation system (SAR), realizing a management principle on a deviation.

As follows from stated, working out of full factorial model of the tractor diesel engine represents enough challenge demanding definition of values of factors of model on the basis of natural experiment.

Dynamic properties of the tractor diesel engine as one of objects of management SAC engine-transmissionwheels can be presented also typical non-periodic dynamic a link of the first order [3, 5, 6, 20]:

$$T\frac{d\varphi}{dt} + \varphi = K \cdot \mu - f(t),$$

Where: *T* - a constant of time of the engine;  $\varphi$  - relative change of angular speed of a shaft of the engine;  $\mu$  - relative moving he dosing out lever the fuel pump; *To* - factor of strengthening of the engine on a course of regulating body; *f*(*t*) - the dimensionless deviation of angular speed caused by change of variable making external loading.

In the absence of fluctuation of resistance f(t) of last expression in the operational form we will receive:

$$(Tp+1)\varphi = K\mu$$
,

and it also is the equation non-periodic a link of the first order with transfer function:

$$W(p) = \frac{\varphi(p)}{\mu(p)} = \frac{K}{Tp+1}$$

which values of parameters define dynamic properties of the engine in transitive operating modes.

At equipment of the diesel engine by modern systems of giving of fuel, for example, «Common rail», «Unit Injection» with electronic control by direct injection of

fuel in engine cylinders, modelling of the characteristic of the engine depends on the mode of the stabilization supported in given movement by an automatic regulator of the engine. Most often at the established movement on гоне technological agricultural unit, for example, harvest, the mode of stabilization of capacity of the engine, and for the transport unit - a mode of stabilization of speed, or a mode of minimization of the expense of fuel can be provided. At engine modelling are in that case necessary external and partial high-speed characteristics of the engine or the complex characteristic (Fig. 3) and algorithm of work of the most automatic control mean the engine. And, at a choice for a control system, for example, a mode of minimization of the expense of fuel, the block of engine management and transmission the cars working synchronously, those from possible at current loading and speed of movement choose modes of the engine and the transfer relation of transmission, at which the engine mode will come nearer as much as possible close to a line  $a\delta$  on the complex characteristic (Fig. 3), it means, that the control system will change also a high-speed mode of the engine, and the transfer relation of transmission [7, 8, 18, 19, 20].

At creation of the mobile car it is necessary to estimate its indicators of dynamics, quality of transients in system engine-transmission-wheels to installation, dynamic loadings of transmission on which judge level of operational properties of the mobile car and efficiency of accepted constructive decisions.

The choice of structure, parameters, laws and algorithms of a control system of the engine, transmission and wheels of the created mobile car, at mathematical modelling of processes in system engine-transmissionwheels is made in a program application by the task of initial data on the blocks concerning corresponding subsystem of system engine-transmission-wheels.

At the task of parameters of the external high-speed characteristic of the diesel engine are used or S.R Lejderman's formulas, or regression polynomial model to nth order, received by processing of experimentally removed characteristics of the engine. For engines with non-monotonic course of curves of capacity and the twisting moment, in case of turbo-supercharging application in diesel engines, for example with several anti-proof readers or at to system of giving of fuel Common Rail, it is used regression polynomial model to 5th order, received by processing of experimentally removed characteristics. The model can be constructed by means of a program application of the mathematical analysis of graphic diagrams AGrapher.

One of problems of modelling of the engine as a part of general model engine-transmission-wheels consists in necessity on each step of integration of the differential equations describing movement of the mobile car, to define a site of a current working point of the engine on its characteristic. The same problem is actual and at creation SAC by transmission if the engine is not equipped by the loading gauge. Therefore the expressions allowing on current values of positions of the lever or a pedal of management by giving of fuel are necessary, to define the current partial high-speed characteristic and twisting moment of a diesel engine on current angular speed of its shaft.

Initial data which are necessary for setting before the beginning of modelling of the diesel engine with all modes a regulator in fuel pump, include the following:

$I_{J}$	_	The	moment	of	inertia	of	the	engine,
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$$M_{\min}$$
 – The twisting moment on is minimum steady turns of the engine,

- $n_{\min}$  Is minimum steady frequency of rotation of a shaft of the engine,
- $M_{\rm max}$  The maximum twisting moment of the engine,
- $n_{\max}$  Frequency of rotation of a shaft of the engine at the maximum moment,
- $P_{\text{max}}$  Maximum engine rated power,
- $n_{p_{\text{max}}}$  Frequency of rotation of a shaft of the engine at the maximum capacity,
- $\beta_n$  Factor of non-uniformity of regulator fuel pump,
- $n_{xx_{max}}$  The maximum frequency of rotation of a shaft of the engine idling,
  - y A share from a full speed of the lever of the task of giving of fuel (from 0 to 1),
  - z A share from a full speed of a pedal of gas at the beginning (from 0 to 1).

At lever installation fuel supply not on a maximum, and in some intermediate position y where  $0 \le y < 1$ , a working branches of a regulator is in parallel displaced towards smaller frequencies of rotation and it becomes insignificant more flat according to dependence for the concrete engine, (Fig. 5).



**Fig. 5.** A working branch of a regulator of the characteristic of a diesel engine at intermediate position of the lever of fuel supply

In (Fig. 6) diesel engine work on various modes at which the minimum expense of fuel (the shaded area) is shown. Here the moments of necessary switching on the higher and lowest transfers after achievement by shaft of the engine of certain angular speed are shown to remain in the shaded zone [1, 18, 20].



Fig. 6. Area of the minimum expense of fuel

Accepting linear approximation of dependence  $\beta_p$  ( $n_{ymax}$ ), we can write  $k_{\beta p}$  - factor of communication of these sizes:

$$k_{\beta p} = \frac{\beta_{P_{H}} - \beta_{P}}{n_{xx \max} - n_{\min}} = \frac{\beta_{P_{V}} - \beta_{P}}{n_{xx \max} - n_{y\min}}.$$
 (1)

For example, for diesel engines with TNWD with all modes a regulator of universally-agricultural tractors:

$$\beta_P \approx 0.12, \quad k_{\beta_P} \approx \frac{0.18 - 0.12}{230 - 150} = \frac{0.06}{80} = 0.00075.$$

From last expression for factor of non-uniformity of a regulator follows at intermediate position of the lever of the task of giving of fuel *y*:

$$\beta_{Py} = \beta_P + k_{\beta P} \cdot \left( n_{xx \max} - n_{xx y \max} \right). \tag{2}$$

At diesel engine work on transitive modes the effective twisting moment of the engine decreases in comparison with the high-speed characteristic that is considered by factor  $\gamma_m$  then

$$M_{\partial i} = M_{\partial cmi} \cdot \left( 1 - \gamma_m \cdot \frac{d\omega_{di}}{dt} \right) = M_{\partial cmi} \cdot \left( 1 - \gamma_m \cdot \varepsilon_{di} \right), \quad (3)$$

where:  $\varepsilon_{di}$  - angular acceleration of a shaft of the engine.

At the set position of the lever of giving of fuel *y* it is defined corresponding value of frequency of idling:

$$n_{xx y \max} = n_{\min} + y \cdot (n_{xx \max} - n_{\min}); \text{ And angular}$$
  
speed is equal  $\omega_{xx y \max} = \frac{\pi \cdot n_{xx \max}}{30}.$  (4)

The factor  $k_{p}$ , a characterizing corner of an inclination flowing working branches, is equal:

$$k_{p} = \frac{2 \cdot M_{P_{\max}}}{\left[\beta_{P} + k_{\beta p} \cdot \left(n_{xx \max} - n_{xx y \max}\right)\right] \cdot \left(n_{xx \max} + n_{P_{\max}}\right)}.$$
 (5)

As according to earlier resulted formulas on an external branch of the characteristic

$$M_{y\max} = M_{P\max} \cdot \left[ a + b \cdot \frac{n_{y\max}}{n_{P\max}} + c \cdot \left( \frac{n_{y\max}}{n_{P\max}} \right)^2 \right],$$

then for partial working branches  $M_{di} = k_p \cdot (n_{xy \max} - n_{di})$ , and current capacity of engine

$$P_{di} = M_{di} \cdot \omega_{di}. \tag{6}$$

At diesel engine functioned on partial working branches  $n_{xymax} \ge n_{di} \ge n_{ymax}$ . We will find  $n_{xymax}$ , considering, that the point  $(M_{ymax}, n_{ymax})$  simultaneously belongs also to an external branch and partial a working branches of regulator of the high-speed characteristic. Then the following record is fair:

$$a \cdot M_{P_{\max}} + b \cdot M_{P_{\max}} \cdot \frac{n_{y_{\max}}}{n_{P_{\max}}} + c \cdot M_{P_{\max}} \cdot \left(\frac{n_{y_{\max}}}{n_{P_{\max}}}\right)^2 = k_p \cdot n_{xy_{\max}} - k_p \cdot n_{y_{\max}}.$$
(7)

If to accept an assumption that  $k_p = const$ , then, having designated

$$c \cdot \frac{M_{P\max}}{n_{P\max}^2} = A; \quad \left(k_p + b \cdot \frac{M_{P\max}}{n_{p\max}}\right) = B;$$

$$\left(a \cdot M_{P\max} - k_p \cdot n_{xy\max}\right) = C. \tag{8}$$

From expression (7) we will receive:

$$A \cdot n_{y\max}^2 + B \cdot n_{y\max} + C = 0 \text{ Or } n_{y\max}^2 + \frac{B}{A} \cdot n_{y\max} + \frac{C}{A} = 0.$$
(9)

The decision of the received quadratic (9) will look like:

$$n_{y\max} = -\frac{B}{2 \cdot A} - \sqrt{\frac{B^2 - 4 \cdot A \cdot C}{4 \cdot A^2}}.$$
 (10)

Knowing  $n_{ymax}$ , we define  $M_{di}$  and  $P_{di}$  on corresponding expressions for partial working branches of the high-speed characteristic.

#### CONLUSIONS

At management of a foot pedal of fuel supply z (*t*) and at the position task y a control lever of supply of fuel calculation is conducted in the following sequence.

If moving of a pedal of giving of fuel submits to some law z (t) in time or z  $(\omega_{\partial t})$  as current angular speed of a cranked shaft of a diesel engine, it means, that to value of position of the lever y some share from the remained course of the lever (1-) z, fuel supply pressed against the stop. In the latter case at = at + (1-).1 = 1, that corresponds to the external high-speed characteristic of a diesel engine. In this case on each step of integration new value at = at + (1-).z (t) pays off and earlier received expressions operate.

At modelling of movement of the mobile car on each step of integration of the differential equations describing dynamics system of engine-transmission-wheels, it is necessary to define "site" of a working point of a diesel engine, that is:

- the equation flowing working branches on at(t) and z(t),
- value of current torque  $M_{\partial i}$  on current frequency of rotation of a shaft of the engine  $n_{\partial i}$  or its angular speed  $\omega_{\partial i}$ .

Thus, the developed variants of mathematical descriptions of the diesel engine are presented, and the variant choice is defined by problems of concrete research of dynamics of the machine tractor unit.

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# MODELOWANIE SILNIKA WYSOKOPRĘŻNEGO W BADANIACH DYNAMIKI MASZYNOWYCH AGREGATÓW CIĄGNIKOWYCH

Streszczenie. W publikacji przedstawiono matematyczny opis silnika wysokoprężnego maszynowych agregatów ciągnikowych szerokiego przeznaczenia w badaniach ich dynamiki przy opracowywaniu nowych środków technicznych. W artykule rozpatrzono podstawy metodyczne modelowania silników wysokoprężnych w szerokim aspekcie dynamiki agregatów ciągnikowych. Przedstawiono opracowane warianty matematycznych modeli silnika wysokoprężnego. Wybór wariantu określono zadaniami i celem konkretnych badań dynamiki maszynowego agregatu ciągnikowego.

Słowa kluczowe: maszynowy agregat ciągnikowy, modelowanie dynamiki, matematyczny opis silnika wysokoprężnego, badanie dynamiki.

# Quantitative time management methods in project management

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Summary. The paper presents an algorithm for the calculations of a network of relationships using the critical path method, the correlations for the total, free, conditional and independent slack time, the correlations for all kinds of relationships between the tasks: FS, SS, FF, SF. An example of a network with modifications has been presented.

K e y w o r d s : project management, quantitative methods, critical path method

#### INTRODUCTION

Quantitative methods of project management date back to the beginning of the XX century. Already before WWII a Pole, Karol Adamiecki, created the foundations of the quantitative time management in projects and rhythmical production. H. Gantt, F. Taylor, Ch. Babbage, the team of the professor P. Blacket, also contributed to the development of the quantitative method. Another step was the creation of the critical path method by Du Pont engineers and the simultaneous production of the Polaris ballistic missile along with the development of the PERT method. These methods could not advance due to a lack of calculation tools. Ever since personal computers advanced sufficiently the quantitative methods should have been sidetracked, yet this is not the case. Despite availability of sophisticated software for project management the software is not properly used. There is no knowledge on the mathematical quantitative methods used in the software. On many occasions huge projects involving over 10 thousand tasks are planned manually and the project management software is merely there for printing purposes. The plans are prepared due to the requirements of public procurement or insurance companies but later they are sent directly to the archives and the project is managed by intuition. The aim of this paper is to acquaint the reader with the basics needed to employ the quantitative methods of managing time in

project management and prepare the reader to use the software based on these methods.

## WORK BREAKDOWN STRUCTURE

When organizing projects it is necessary to determine the aim of the task, the basic project checkpoints (milestones), the tasks that will be realized, duration of these tasks, used resources, expenses etc. After determining of the project aim a multilevel work breakdown structure is created (WBS) formed through a decomposition of the subsequent elements aiming at putting all the tasks together that will be realized during the project. In order o identify the individual tasks the structure is encoded.

The work breakdown structure constitutes the basis for work planning, estimation of resources and expenses, determination of the scope of works, determination of the development path and the inspections, assignment of responsibility, risk identification and introduction of changes. The benefit resulting from the application of WBS is easy retrieval of information from previous projects with similar tasks, processes, assembly and components, the possibility of determining of the purchasing needs and specifications, the possibility of using joint integrated management system - joint databases, documentation, quotations, budgets, technical drawings, financial accounting systems as well as the possibility of performing of the cost analysis and other data.

The work breakdown structure is used on many managerial levels. Depending on the needs of the recipient it is possible to analyze information on different levels of the structure taking into account their different detail level. The highest level managers need consolidated information available at higher WBS levels while the lower level employees are interested in details characteristic of the lower levels.

The responsibility for the preparation of the work breakdown structure is on the side of the project manager. The WBS may be created through a top-down method (method dictated by the higher levels of authority), when the main scaffolding of the structure is created by the project manager and higher level managers and the detailed work is defined by the line managers. The bottomup method consists in preparing of the structure from detail to general. This method is usually applied when the structure is created based on the already existing projects, the results to be achieved are known and the structure is composed of known elements. The structure is developed by employees of lower level and people responsible for the work realization and the adjustments and acceptance is done by the project manager. It is worth involving important interested parties such as clients in the WBS creation.

An example of work breakdown structure has been presented below.

Level 1 Level 2 Level 3 Level 4 J. J. Ţ **0.** Building a house **0.1.** Foundation **0.1.1.** Digging the foundation 0.1.2. Shuttering 0.1.3. Pouring concrete **0.2.** Construction of a building 0.2.1. Construction of a basement ceiling 0.2.2. Building walls 0.2.2.1. Building partition walls 0.2.2.2. Building load bearing walls **0.2.3.** Construction of a tie beam **0.3.** Construction of a roof 0.3.1. Fixing the ceiling **0.3.2.** Construction of the roof elements 0.3.3. Roofing **0.4.** Installations 0.4.1. Water and sewage **0.4.2.** Central heating 0.5. Project management 0.5.1. Project organization 0.5.2. Planning 0.5.3. Project supervision 0.5.4. Documentation

## NETWORK METHODS OF PROJECT MODELING

After the task has been identified a network model of a project is created. The tasks are set one after another in a technological order of performance. The basis of the network is digraphs i.e. ordered sets of vertices (nodes) and arches (edges) with one source and one exit:

$$G = \{ \langle W(G), L(G) \rangle \}$$
(1)

The network is identified as a set of ordered threes:

$$S = [W, L, \varphi]$$
(2)

$$\varphi \colon W \ge W \to L \tag{3}$$

where:

- G digraph,
- W set of graph vertices,
- *L* set of graph branches,
- S network,
- $\varphi$  relation.

In networks the arches are assigned weights. An ordered pair on the graph is presented with arrows connecting individual nodes oriented from the beginning of the arch to its end. The length of the graph arches does not represent the actual lengths between the edges but only represents the order of their occurrence. In the graphs showing the realization of the projects paths are determined i.e. such sets of vertices in which they occur only once and in which the arches are different. The longest path in the network is referred to as sensitive path, critical path or decisive sequence of tasks. The projects can be presented in the form of graphs where the vertices are assigned events and the arches are assigned tasks (tasks at the edges of the graph) or where the vertices of the graph are assigned tasks and the edges represent their technological order of performance (tasks in the graph nodes). The arches in these graphs are assigned weights denoting, for example, the duration of the task. The events (tasks) are assigned a date. In order to unequivocally determine the graph we only need to enter the set of ordered pairs and the values of the nodes or arches. The neighborhood matrices are determined too (for the edges or the vertices) or the incidence matrices (of the neighborhood of edges and arches). Additionally for identification of the network the weight matrix has to be specified. In this paper only simple network without multiple edges will be considered. One pair of nodes will always be assigned an arch. Cyclic networks (with loops) i.e. edges connecting the same vertices will not be considered.

# CRITICAL PATH METHOD

Critical Path Method (CPM) has been discussed in many publications, yet these publications present only the simplified form of calculation. Calculation methods are not presented for other relations than the finish of the predecessor task-beginning of the successor task. Not all the types of slack times (only total and free) are discussed. The principles of Project modeling through the Critical Path Method are thus worth revisiting.

The Critical Path Method is a fully deterministic method. It assumes both the deterministic value of dura-

tion of individual tasks and the deterministic construction of the network of relations.

The CPM was developed going on the assumption that there are no limited resources. Such networks can obviously undergo optimizations in terms of resources availability upon construction of the network taking into account the logical sequence of tasks only.

The network calculations are performed in two stages. In the first stage (forward calculations) the earliest dates of the occurrence of all the events are set. In the second stage the latest dates of the occurrence are set. Below the algorithm of the network calculation has been presented.

#### Network calculation algorithm

• Stage I

- 1. Setting the start date of the project
- 2. Setting the earliest start dates of all tasks
- 3. Setting the earliest finish dates of all tasks
- 4. Setting the finish date of the project

• Stage II

- 1. Setting the latest finish date of the project (most frequently this date is set as equal to the earliest finish date of the project)
- 2. Setting the latest finish dates of all tasks
- 3. Setting the latest start dates of all tasks
- 4. Setting the slack time
- 5. Setting the critical path

In the calculations the following symbols have been used:

WS early start,

- WK early finish,
- *PS* late start,
- *PK* late finish,
- ZC total slack,
- ZS free slack
- ZW conditional slack,
- ZN independent slack,
- *t* duration of task,
- *p, poprz* predecessor task
- *n, nast.* successor task

Upon performing of the calculations for the assumed durations the optimization of the network is carried out taking into account the availability of resources and other adopted criteria.

In the first stage the start date of the project is set. In non-computer calculations the start date of the project is zero. Computer software assumes the start date of the project as a date given by the operator.

Another step in the calculation of the first stage is setting the earliest dates of all events. For each task the earliest start date needs to be set. Then the earliest finish date WK of this task is set, which is equal to the sum of the earliest start date WS and the duration of the task t. If, in the analyzed event, several tasks are finished we need to calculate the finish date of each of them and as the date of occurrence of the event we need to assume

the greatest number because the successor task may start when the longest of the predecessor task is finished.

$$WK = max (WS + t) \tag{4}$$

Upon the completion of the calculations for all the tasks we obtain information on the earliest finish date of the project.

The second stage of the calculations begins with setting the latest admissible finish date of the project. Most frequently, the earliest finish date of the project is assumed (the same as in the first stage of the calculations). This could also be a different date – a date set by a directive. The next step is setting the latest dates for the occurrence of all events. For each task first we need to set its latest finish date *PK*. Then the latest start dates *PS* of the tasks are set. The latest start date of a task *PS* equals the difference between the latest finish date of the tasks are started we calculate the latest start dates of these tasks and as the latest date of the event occurrence we assume the least number. This ensures completion of the project in the assumed time.

$$PS = \min\left(PK - t\right) \tag{5}$$

Upon completing the calculations for the tasks we can determine different types of slack times. The total slack time ZC is a minimum determined based on the calculations for the start and finish dates of the tasks. The total slack time can be determined as a difference between the latest finish date of a task and the earliest finish date of the same task. The total slack time can also be determined as a difference between the latest start date of a task and the earliest start date of the same task. The total slack time value is assumed as the least value of the two calculations.

$$ZC = min \{(PK - WK), (PS - PS)\}$$
(6)

The total slack time is common for all tasks in one sequence. If it is used by the earlier tasks the later tasks will lose this slack time. It comprises all other slack times. If it is zero then the other slack times are also zero. The task under analysis is performed as early as possible. The subsequent task is performed as late as possible. The total slack time is also a difference between the latest start of the successor task (if there are several successor tasks we should choose the least value) and the earliest finish of the actual task.

Free slack time ZS is a difference between the earliest start date of the successor task (if subsequently there are several successor tasks we should choose the least value) and the earliest finish date of the actual task. The predecessor task is performed as early as possible. The actual task is performed as early as possible. The successor task is performed as early as possible.

$$ZS = min (WS_{nast}) - WK$$
<sup>(7)</sup>

This slack time can be used and the successor tasks will not lose their slack time, yet the predecessor task must be performed in the earliest possible time.

Conditional slack time ZW is a difference between the minimum value of the latest start dates of the successor tasks and the sum of the maximum value of the latest finish dates of all predecessor tasks and the duration of the task for which the conditional slack time is calculated. The predecessor task is performed as late as possible. The actual task is performed right after the predecessor. The successor task is performed as late as possible.

$$ZW = min \left(PS_{nast}\right) - \{max \left(PK_{nant}\right) + t\} \qquad (8)$$

The slack time allows performing the predecessor tasks at any time. The use of this slack time forces the performance of the successor task at the latest time i.e. all slack times of the successor tasks in this sequence will be used. The conditional slack time comprises independent slack time.

Independent slack ZN is a difference between the minimum value of the earliest start dates of all successor tasks and the sum of the maximum value of the latest finish dates of all predecessor tasks and the duration of the task for which the conditional slack time is calculated. The predecessor task is performed as late as possible. The actual task is performed right after the predecessor. The successor task is performed as early as possible.

$$ZN = min (WS_{nast}) - \{max (PK_{nanz}) + t\}$$

This slack time provides information in what time the task can be performed without influencing the performance of the successor and predecessor tasks. They can be performed in times determined in the calculations and the independent slack time will remain intact. This slack time can assume negative values, which means that it is impossible to perform the actual task as late as possible and the successor task as early as possible. The negative value indicates how many units of time the successor task needs to shift to be after the actual task.

The longest sequence of tasks in duration in the whole project is the critical path. This is at the same time a sequence that does not have slack times or has the least slack times of all sequences of tasks. The tasks on the critical path are subject to particular supervision on the side of the project manager. If any of the tasks on this path extends in time then the whole project will extend in time by the same amount of time. If the tasks on this path are shrunk in time the whole project may be finished earlier (but not always) by the time the critical path was shrunk. Upon shrinking of the critical path other paths may appear that may be longer than that being shrunk. In such a case the critical path becomes the longest path in the whole project. In a project there may be several critical paths. Then, completion of a project is dependent on the tasks on each of these paths.

In a project the tasks can be correlated in different ways. The basic and default relationship is the finishstart (FS) relationship. With this relationship when the predecessor task is finished we can start the successor task. The start-start (SS) relationship allows placing the start of the successor task after the start of the predecessor task. In the finish-finish relationship after finishing of the predecessor task finishing of the successor task takes place. The most controversial is the start-finish (SF) relationship. Here, after the start of the technologically predecessor task the finish of the technologically successor task is placed. Obviously, the first in time will be the task that finishes first, yet this finish depends on the start of the task that is placed as the successor in time. An example could be the change of the shifts of the security personnel. The employee can only end his shift if the next employee comes in to replace him.

Below complete relations have been presented for the determination of dates and slack times in the network.

Each successor task can be shifted against the predecessor by a relative or absolute period of time. Super-



Fig. 2. Types of slacks for the same task presented in the time scale.

imposing of rigid time schedules of the task realization is also possible.

# Dependences of the calculations for different relations in the network

• Stage I of the calculations

Calculating the earliest start for the successor task

For the relationship FS:
$$WS_n = WK_p + \Delta$$
 (9)

For the relationship 
$$SS:WS_n = WS_n + \Delta$$
 (10)

For the relationship 
$$FF:WS_n = (WK_n + \Delta) - t_n$$
 (11)

For the relationship SF: $WS_n = (WS_p + \Delta) - t_n$  (12)

Of all the  $WS_n$  value select the greatest value

#### Calculating the early finish of the successor task

$$WK_n = WS_n + t_n \tag{13}$$

• II stage of the calculations

## Calculating the latest finish of the predecessor task

For the relationship FS:  $PK_p = PS - \Delta$  (14)

For the relationship SS:
$$PK_p = (PS_n - \Delta) + t_p$$
 (15)

For the relationship  $FF:PK_p = PK_n - \Delta$  (16)

For the relationship SF: $PK_p = PK_n - \Delta + t_p$  (17)

Of all the  $PK_{p}$  values select the least value

 $PS_p = PK_p - t_p$ 

# Calculating the latest start of the predecessor task

# Total slack time

$$ZC = \min \left\{ \left( PS_p - WS_p \right), \left( PK_p - WK_p \right) \right\}$$
(19)

#### Free slack time

For the relationship  $FS:ZS = (WSn - WKp) - \Delta$  (20)

For the relationship 
$$SS:ZS = (WSn - WSp) - \Delta$$
 (21)

For the relationship 
$$FF:ZS = (WKn - WKp) - \Delta$$
 (22)

For the relationship 
$$SF:ZS = (WKn - WSp) - \Delta$$
 (23)

Of all the calculated free slack times select the least (12) value

Example of the network of relations calculated with critical path method has been presented in figure 1.

The calculations have been performed with the critical path method.

# CONCLUSIONS

There are many methods of quantitative modeling of projects. Aside from the critical path method such methods were developed as the PERT method that takes into account the probabilistic characteristics of the task duration, the fully probabilistic GERT method, the method of critical chain taking into account only time and delay management or the earned value method whose purpose is to manage the realization of the project. A variety of methods optimizing the project have also been developed.

This paper aimed at consolidating the knowledge related to the basics in the network calculations with the use of the critical path method. It is the computer tools for project management that most frequently use this method.



(18)

Fig. 1. Example of the network of relations drawn with the method activities on nodes.

The exploration and full comprehension of the course of the calculations will enable a successful understanding of computer software for project management.

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#### METODY ILOŚCIOWE ORGANIZACJI CZASU W ZARZADZANIU PROJEKTAMI

Streszczenie. W pracy przedstawiono algorytm obliczeń sieci relacji używając metody ścieżki krytycznej, korelacji dla sumarycznego, wolnego, warunkowego i niezależnego czasu lużnego, korelacji dla wszystkich rodzajów relacji między zadaniami: FS, SS, FF, SF. Zaprezentowano przykład sieci z modyfikacjami.

Słowa kluczowe: zarządzanie projektami, metody ilościowe, metoda ścieżki krytycznej.

# In-use investigations of the changes of lubricant properties in diesel engines

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S u m m a r y. The paper discusses the results of comparative investigations of the changes of the dynamic viscosity and dielectric constant of lubricants as a function of temperature and fuel consumption in diesel engines fueled with Ecodiesel Plus 50B under actual operating conditions. The oil change intervals recommended by the engine manufacturers due to a difficult to define variability condition do not always correspond with the actual needs. When realizing a periodical diagnosis of the selected oil parameters for given operating conditions we can determine new criteria, which would be economically justified – particularly in professional applications.

Key words: diesel fuels, engine oils, dynamic viscosity, dielectric constant.

## INTRODUCTION

The basic functions of the engine oil are: lubrication, cooling, cleaning, engine sealing etc. [17]. Very difficult to identify in practice are the changes of the lubrication conditions of critical pairs resulting from a continuous deterioration of the engine oil parameters, dissolution and dispersion of contaminants and fuel leakage through piston-piston and ring-piston sleeve pair [16]. That is why during operation under actual conditions it is recommended to frequently monitor the condition of the engine oil in the whole period between oil changes. The oil change intervals recommended by the manufacturers due to a difficult to define operating conditions variability do not always reflect the actual needs. By carrying out periodical comparative tests of the properties of the lubricants in the oil sump at given operating conditions we can determine new criteria of oil change and obtain measurable benefits in the form of savings in the operating costs [2].

The design, technological history of the materials and parts in the friction pairs as well as mutual triboligical interactions during operation – very much dependent on the quality of the applied oils and fuels – determine the course of the decrement processes in the friction pairs of diesel engines fitted in vehicles and self propelled machinery. The selection of oil for the central lubrication systems, including, in particular its properties, for the actual operating conditions may have key impact on the durability and reliability of diesel engines [2, 6, 7, 13, 17, 18, 19].

An important problem related to the durability of sliding critical pairs in diesel engines in operation, indicated by many authors in recent publications is the application of bio- and eco- fuels that used according to the requirements of the increasingly more stringent emission standards [1, 9, 10, 11, 20, 21, 22, 23]. Diesel engines are particularly sensitive to fuel quality and the use of such fuels can lead to changes in the lubrication parameters (not only in the kinematic pairs of the fuel system but also in the centrally lubricated kinematic pairs) of consequences that are difficult to determine in terms of the deterioration of the whole engine [6, 7, 8, 9, 10, 11].

In relation to the presented conditions, the authors attempted to explain in comparative investigations whether the amount of used fuel under actual conditions of operation has influence on the changes of the rheological and quality properties of the engine lubricants in diesel engines fitted in farm tractors. The authors attempted to explain whether the observed changes of the selected parameters of the engine oil resulting from the consumption of a certain amount of fuel may lead to the verification of the oil change intervals and in extreme cases to a development of pathological wear processes in the critical friction pairs – particularly sliding friction pairs.

#### **OBJECT AND METHODS OF INVESTIGATIONS**

The object of the investigations were oil samples taken between the oil change intervals from 5 Z 8602.1

engines (engine operation time to date approximately 300÷600 mth after rebuild – Ursus farm tractors) and 5 T4/SIIIB engines utilizing the PowerTech Plus technology (engine operation time to date approximately 700÷1000 mth, new engines John Deere 7430) fueled with the same kind of fuel– ON Ekodiesel Plus 50B.

Right before the tests were initiated the lubricating systems were filled with oil recommended by the engine manufacturers [5, 14]:

- U engines (Z 8602.1) SAE 15W/40, API CG-4, ACEA E2/B2/A2,
- JD engines (T4/SIIIB) SAE 15W/40, API CI-4, ACEA E4.

Then, the diagnostics of the engine condition was performed as per the manual. Based on the obtained results of the inspection the engines were deemed as technically operative.

All the engines assigned for comparative investigations were operated in similar weather, soil and terrain conditions - in the periods from the end of March to the end of November (agro-technical season) 2010 in two adjacent villages. The engines were used typically for their power output class. The oil samples were taken according to a preset procedure - the same for each engine. The first sample was taken from the oil container where it was stored before application. Subsequent samples were taken every 200 dm3 of the consumed fuel until next oil change. The samples were taken through the dipstick access by a syringe ending with a rubber hose  $(50 \cdot 10^{-6} \text{ m}^3)$ in capacity) with the accuracy of  $5 \cdot 10^{-7}$  m<sup>3</sup>, immediately after the tractor ended operation. Immediately after the samples were taken the syringe and the hose were thoroughly cleaned in a solvent and dried. The oil decrement was topped up. In the period when the experiment was conducted the amount of consumed fuel was recorded based on the readouts of the fitted flow meters with the accuracy of +1% from the measured value.

For the determination of the viscosity a digital rotary viscometer was used (Brookfield DV-II+ with an ultrathermostatic chamber, PC computer controlled based on Rheocalc 32 software). The measurement was conducted according to the standard [24] and recommendations of the manufacturer of the viscometer with the accuracy of  $\pm 10^{-2}$  mPa·s [3]. For the determination of the qualitative changes of the oil a Lubrisensor was used. Thanks to the measurement of the relative changes of the value of dielectric constant  $\varepsilon$  (with the accuracy of  $\pm 10^{-1}$  F·m<sup>-1</sup>) the Lubrisensor recognized 3 groups of engine oil operation contaminants (I group- oxides, sediments, dirt, fuel combustion products, acids; II group - water, coolant, metal parts; III group – fuel). Dielectric constant  $\varepsilon$ grows or decreases proportionally to the change of the concentration of the contaminants present in the fuel. The direction of the indicator towards '+' or '-' and the readout determine the group of the contaminants and their amount. The assessment of the conditions of the tested oil consists in calibrating of the device on a base sample (fresh oil) and measuring of the changes of dielectric constant  $\varepsilon$  for the tested samples taken from the engine [4, 12]. In the whole test cycle the total of 30 oil samples were taken from the U engines (6 from each engine) and 45 samples from the JD engines (9 from each engine). For each of the taken samples the measurement of the changes in the  $\varepsilon$  value in the temperature of 293K was carried out three times as well as the measurement of the dynamic viscosity for the temperatures in the range (273÷368) K stepwise every 5K. Next, the average values and standard deviations were calculated. The obtained results were subjected to statistical analysis on the significance level of  $\alpha = 0.05$ .



Fig. 1. Comparison of the relative regression lines of the changes of the dielectric constant of the tested engine lubricants as a function of fuel consumption (constant measuring temperature T = 293 K)

## DISCUSSION OF THE TEST RESULTS

Based on the statistical analysis of the test results a significant influence of the amount of consumed fuel on the changes of the dielectric constant was observed of the engine oils SAE 15W/40, API CG-4, ACEA E2/ B2/A2 and SAE 15W/40, API CI-4, ACEA E4. A very strong positive correlation was observed between the changes of the  $\varepsilon$  values and the amount of consumed fuel (Fig. 1). The comparison of the direction coefficients of the lines of regression indicates that the unit increment of the  $\varepsilon$  value as a function of consumed fuel for the engine lubricant SAE 15W/40 API CG-4 (Fig. 1, dotted line) is approximately 3 times greater than for the engine lubricant SAE 15W/40, API CI-4 (Fig. 1, solid line).

During the comparative in-use tests of the qualitative changes of the engine oils with the use of Lubrisensor in the case of all the samples taken directly from the oil pan in the period of operation under analysis only contaminants from group I were detected. No contaminants from groups II and III (water, coolant, metallic parts, fuel) were detected by the device. This may confirm the earlier formulated assumption regarding the conditions of full parametric usability of the engines, adopted in the beginning of the comparative tests after carrying out of the diagnostic procedures as recommended by the manufacturer. An important effect of the conducted tests is the increment of the value of the dielectric constant clearly seen in Fig. 1 (as compared to the base oil) already in the first samples taken from the engines after consuming approximately 200 dm<sup>3</sup> of fuel. Such a significant change already after the first examination may indicate an excessive amount of contaminants (exhaust carbon, deposits, sludge) in the interior parts of the engine and oil ducts and indicate the need for flushing of the system before oil change.

Fig. 2 presents the sequential graphs of the changes in the dynamic viscosity of the monitored engine oils as a function of temperature and fuel consumption obtained based on the results of the performed in-use tests.

In the whole agrotechnical season of the field works and transport works with the fuel consumption of approximately 2400 dm<sup>3</sup> (for the JD engines) and approximately 1200 dm<sup>3</sup> (for the U engines) the authors did not observe



Fig. 2. Sequential charts of the changes in the dynamic viscosity of the tested oils as a function of temperature and consumed fuel: U engines (SAE 15W/40 API CG-4), JD engines (SAE 15W/40, API CI-4)



**Fig. 3.** Surface charts with regression equations of the changes in the dynamic viscosity of the engine oils as a function of temperature and consumed fuel: U engines (SAE 15W/40 API CG-4), JD engines (SAE 15W/40, API CI-4) (interval estimation for the conditions of start-up and cold operation in the temperature range of 273K to 313K)



**Fig. 4.** Surface charts with regression equations of the changes in the dynamic viscosity of the engine oils as a function of temperature and consumed fuel: U engines (SAE 15W/40 API CG-4), JD engines (SAE 15W/40, API CI-4) (interval estimation for the conditions of start-up and cold operation in the temperature range of 343K To 368K)

an excess of the admissible values of the dynamic viscosity (Fig. 3 and 4) and the dielectric constant (Fig. 1) as compared to the fresh oil.

Based on the discussed nature of the changes of the values of the dynamic viscosity and the dielectric constant of the monitored oils: SAE 15W/40 API CG-4 and API CI-4 as a function of the amount of consumed fuel a supposition was formed that the oil change interval be extended until the boundary values are reached defined in the variability range of  $\pm 25\%$  (dynamic viscosity) [2] and (3,5÷4,0) F·m<sup>-1</sup> (dielectric constant) [15].

#### CONCLUSIONS

- 1. The changes in the dynamic viscosity of the oil show a strong (U engines) and very strong (JD engines) negative correlation as a function of time and amount of consumed fuel. The greatest observed unit drops of the dynamic viscosity, as a function of temperature, were observed on the base samples (fresh oil) and the smallest on the samples right before the oil change. In the temperature range  $(273 \div 313)$  K – for start-up and cold engine operation- the unit drop in the dynamic viscosity as a function of the consumed fuel in the T4/ SIIIB engines is approximately 40% smaller and as a function of temperature approximately 20% greater than in the Z 8602.1 engines. In the range of operating temperatures (343÷368) K the unit drop in the dynamic viscosity as a function of consumed fuel in the T4/SIIIB engines is approximately 3 times smaller and as a function of temperature approximately 14% greater than in the Z 8602.1 engines.
- 2. The changes in the dielectric constant of the oil in the Z 8602.1 and T4/SIIIB engines indicate a very strong positive correlation as a function of the growth of the consumed fuel. Based on the analysis of the regression model of the relative change of the dielectric constant in the temperature of 293K the authors observed that

the unit  $\varepsilon$  increment as a function of the consumed fuel in the Z 8602.1 engines is approximately 3 time greater than in the T4/SIIIB engines.

3. It is possible to extend the oil change intervals in the SAE 15W/40 API CG-4 and API CI-4 classes in relation to the specifications of the Z 8602.1 and T4/ SIIIB engine manufacturers as the relative change in the dielectric constant is smaller than (3,5÷4)F·m<sup>-1</sup> and the change in the dynamic viscosity in the whole range of analyzed temperatures and consumed fuel does not exceed (25÷30)% as compared to the fresh oil, which is deemed as admissible [6, 7, 24]. An additional argument confirming the purposefulness of this possibility is the fact that in none of the analyzed samples were there any contaminants from groups II and III that are responsible for developing of pathological wear processes in the sliding pairs.

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# BADANIA EKSPLOATACYJNE ZMIAN WŁAŚCIWOŚCI OLEJÓW SMARNYCH W SILNIKACH Z ZAPŁONEM SAMOCZYNNYM

Streszczenie. W pracy omówiono wyniki badań porównawczych zmian lepkości dynamicznej i stałej dielektrycznej oleju smarnego w funkcji temperatury i zużycia paliwa, w silnikach z zapłonem samoczynnym, zasilanych paliwem Ekodiesel Plus 50B w rzeczywistych warunkach eksploatacji. Terminy wymian zalecane przez producentów silników, ze względu na trudną do zdefiniowania zmienność warunków pracy, nie zawsze są zgodne z rzeczywistymi wymaganiami. Realizując okresowe diagnozowanie wybranych parametrów oleju silnikowego, dla określonych warunków eksploatacyjnych, można wyznaczyć nowe kryteria wymiany, co ma ekonomiczne uzasadnienie – szczególnie w zastosowaniach profesjonalnych.

Słowa kluczowe: paliwa do silników z zapłonem samoczynnym, oleje silnikowe, lepkość dynamiczna, stała dielektryczna.

# Application of chromatography to the analysis of quality of RME type biofuels obtained from pure, fresh rapeseed oil and from the waste (previously fried) oil of the same origin

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S u m m a r y. Efficiency of RME production process from waste (previously fried) oil during transesterification with methanol in the presence of KOH (as catalyst) is a function of many variables. In the dissertation it is shown that by proper control of appropriate amount of catalytic reaction substrates as well as thermal conditions and suitable period of process time it is possible to obtain conversion efficiency of waste rapeseed oil similar to the conversion efficiency obtained for pure rapeseed oil. Investigations also confirmed that, from that waste oil, it is possible to obtain RME having physical and chemical properties similar to biodiesel manufactured from pure rapeseed oil. Therefore, the quality of biofuel on the basis of RME obtained from properly treated waste oil may have similar properties to the RME produced from pure (not used for frying or cooking) rapeseed oil.

Key words: biodiesel, biofuels, RME (Rapeseed Methyl Ester), gas chromatography, diesel engine

#### INTRODUCTION

World norms and directives determine the sort of biofuels that are to feed our engines in short term and long term perspective. Up to 2020 these biofuels or biocomponents used for feeding compression-ignition engines are going to be pure biofuels of plant origin or commixtures of such biofuels and derivatives.

The world's best known biofuel is Biodiesel FAME (Fatty Acid Methyl Esters). Taking into account different climate and soil conditions, biofuels of different origins are going to dominate on particular continents [4, 5, 7, 8].

Among basic parameters determining particular biofuel usefulness for feeding self-ignition engines is the arrangement of fatty acids in FAME [9, 14, 15]. Research shows that in FAME, the more oleic acid there is, the more energy in the biofuel [16, 13]. Biodiesel fuel can be a stand-alone one or can be used as bio-component for diesel [2].

# PURPOSE AND SCOPE

After the analysis of knowledge the author stated that the results of studies found in the specialist literature on the possibility of manufacturing RME biofuels from waste oils show that this kind of material may be suitable for biofuel production. However, after in-depth analysis, it appears that the results of individual properties and characteristics of RME are considerably different. The aim of this study was then to determine the effect of thermal influence during frying on the quantity and quality of RME.

At the first stage of the research pure rapeseed oil and the waste (after frying) one was analyzed by gas chromatography. The idea was to check how the structure of fresh oil was changed after frying. The aim of studies was to show, whether quantity and participation of fatty acids was changed after exposure to heat during frying. Another research idea was also to confirm or deny claims presented by other researchers - e.g. Pharma Cosmetic that pyrolysis causes thermal decomposition of fatty acids to acrolein (C<sub>3</sub>H<sub>4</sub>O) and/or whether the thermal conversion may cause changes in mutual content and composition of fatty acids. At this stage of research it would be very important to determine the range of change (in %) of unfavourable compounds in the structure of the fresh oil in comparison to the waste one. Chromatographic analysis covered the identification of fatty acids in the range of decanoic acid, C10:0 to nervonic acid C24:1. The scope included all the fatty acids that can potentially occur in rapeseed oil.

#### RESEARCH METHODOLOGY

<u>Transesterification process.</u> For rapeseed oil transesterification methanol was applied, because it is inexpensive and efficient in the process of transesterification [1, 12]. A catalyst in this chemical reaction was KOH (Potassium hydroxide pure p.a.). Methanolysis was used as the catalyst KOH as it is one of the most efficient catalysts [3, 6, 11]. Transesterification was a one-stage process, at both times between the temperatures of 330- 340K.

Determination of fatty acid esters in the above-mentioned oils were carried out in accordance with PN-EN ISO 5508 standard using a multi-gas chromatograph of Thermo TRACE GC Ultra type. Figure 1 shows the test stand for gas chromatography analysis.



**Fig. 1.** The test stand equipped with a multi-channel gas chromatograph from Thermo TRACE GC Ultra type

The integration of chromatography was established to be such that the peaks from the capric acid methyl ester ( $C_{10:0}$ ) went up to the peak of the lignoceric acid methyl ester ( $C_{24:0}$ ) and nervonic acid methyl ester ( $C_{24:1}$ ). Based on the received marked information below are the formulas of the contents of "C" esters:

$$C = \frac{\left(\sum A\right) - A_{EI}}{A_{EI}} \times \frac{C_{EI} \times V_{EI}}{m} \times 100\%,$$

where:

 $\sum$ A – the entire surface peaks of methyl esters from C<sub>10</sub> to C<sub>24:1</sub>,

 $A_{EI}$  – surface peaks representing heptadecanoic acid methyl ester,

 $C_{EI}$  – used concentrated dilution of heptadecanoic acid methyl ester; in milligrams per milliliter,

 $V_{EI}$  – the volume of the used dilution of heptadecanoic acid methyl ester, in milliliters,

m – mass of the sample, in milligrams.

Esters were produced in the reactor designed and built by the author of this article. This appliance as the only one in Europe is able to produce Biodiesel RME with a full glycerin phase of two hours.

# **RESULTS OF ANALYSIS**

Figures 2 and 3 show RME Biodiesels chromatograms, on which you can observe the number and size of peaks identifying individual esters of fatty acid.

Table 1 shows the results of chromatographic analysis determining the number and composition of fatty acids in the produced RME and - for comparison - in B100 Biodiesel taken from the fuel station BLISKA.

The data in Table 1 show that all the biofuels - due to total amount of fatty acid esters in the RME - meet requirements of EN 14214 standard. Both the biodiesels had similar fatty acid participation. It is worth mentioning that no fatty acids changes occur during transesterification. Both biodiesels consist of the same amount of fatty acid esters as the quantity and number of fatty acids present in oil used as raw material for RME manufacturing. Comparing the number and participation of fatty acids present in RME produced from both oils with the results of RME tests from fuel station "BLISKA", one may conclude that they are identical.

#### SUMMARY AND CONCLUSIONS

On the basis of studies concerning physical and chemical properties of RME obtained from pure and waste



Fig. 2. Chromatogram of RME Biodiesel produced from pure, refined rapeseed oil



Fig .3. Chromatogram of RME Biodiesel obtained from waste (previously fried) rapeseed oil

The name and participation of fatty acid % (m / m)	Chemical formula	Biodiesel from pure rapeseed oil	Biodiesel from waste (fried) rapeseed oil	RME biodiesel from the fuel station BLISKA / *
Capric acid methyl ester	C10:0	0,012	0,016	-
Lauric acid methyl ester	C12:0	0,011	0,014	-
Myristic acid methyl ester	C14:0	0,051	0,064	0,052
Pentadecanoic acid methyl ester	C15:0	0,019	0,024	0,023
Palmitic acid methyl ester	C16:0	4,263	4,759	4,486
Palmitoleic acid methyl ester	C16:1	0,186	0,202	0,265
Heptadecanoic acid methyl ester	C17:0	0,037	0,41	0,112
Stearic acid methyl ester	C18:0	1,482	1,387	1,808
Oleic acid methyl ester	C18:1	58,076	58,171	60,912
Linoleic acid methyl ester	C18:2	19,966	19,812	19,252
Linolenic acid methyl ester	C18:3	9,438	8,892	8,984
Arachidic acid methyl ester	C20:0	0,507	0,457	0,646
Eicosenoic acid methyl ester	C20:1	1,240	1,176	1,721
Behenic acid methyl ester	C22:0	0,239	0,225	0,365
Erucic acid methyl ester	C22:1	0,236	0,279	0,909
Lignoceric acid methyl ester	C24:0	0,096	0,063	0,129
Nervonic acid methyl ester	C24:1	0,112	0,101	0,187
The degree of identification of fatty ad	Σ =99.99 % (m/m)	$\Sigma = 100.00 \% (m/m)$	$\Sigma = 99.85 \% (m/m)$	

Table 1. Composition of fatty acids in the produced biofuels in comparison to B100 Biodiesel from fuel station BLISKA

/\* - Research results G. Wcisło. 2010. "Przetwarzanie biomasy na cele energetyczne"

(fried) rapeseed oil, we can conclude that, in general, the two biofuels are characterized by similar properties. RME produced from waste oil was characterized by composition and participation of fatty acids similar to biofuel obtained from pure oil. The investigations showed that during frying at high temperatures fatty acids were stable and only slightly (up to 2%) changed their structure. This is very valuable information because the properties of FAME type [Fatty Acid Methyl Esters] biofuels depend largely on the amount of individual fatty acids esters in FAME. Further detailed studies have shown that the following properties of RME obtained from waste oil are identical: the value of the heat of combustion, calorific value, initial point of distillation and distillation temperatures range of up to 90% v/v of biodiesel. However, the temperature of final distillation point is unfortunately higher for biofuels from waste oil. RME produced from waste oil has also a slightly worse rheological properties.

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   Europe standard EN ISO 5508.

## ZASTOSOWANIE CHROMATOGRAFII DO ANALIZY JAKOŚCI BIOPALIW TYPU RME UZYSKANYCH Z OLEJU CZYSTEGO ORAZ ZUŻYTEGO

Streszczenie. Sprawność procesu produkcji RME z zużytego (posmażalniczego) oleju w procesie transestryfikacji metanolem wobec katalizatora KOH jest funkcją wielu zmiennych. Wykazano, że sterując odpowiednią ilością substratów katalitycznej reakcji oraz warunkami termicznymi i długością czasu procesu, można uzyskać sprawność konwersji dla zużytego oleju rzepakowego zbliżoną do sprawności uzyskiwanej dla czystego oleju rzepakowego. Badania potwierdziły również, że można uzyskać z oleju posmażalniczego RME o zbliżonych własnościach fizyko-chemicznych do Biodiesla uzyskanego z czystego oleju rzepakowego. W związku z tym jakość biopaliwa RME z zużytego oleju może mieć zbliżone własności do RME wyprodukowanego z czystego (nieprzepracowanego) oleju rzepakowego.

Słowa kluczowe: biodiesl, biopaliwo, RME (Estry metylowe oleju rzepakowego), chromatografia gazowa, silnik wysokoprężny.

# Oil pressure distribution in conical ring gaps

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Summary. The paper deals with oil flow in ring gaps in piston pumps and hydraulic motors. On the basis of the Navier-Stokes equations a formula describing the pressure in the gap has been established. The pressure distribution obtained for confusor and diffuser gaps were presented as functions of oil viscosity and the relative velocity of the piston for its various eccentric positions.

Key words: piston-cylinder of a pump, ring gap, pressure distribution.

## INTRODUCTION

In hydraulic systems there are gaps between adjacent surfaces [1, 2, 4, 5, 21]. The right functioning of modern hydraulic systems largely depends on complex processes occurring in such gaps. Therefore, one of the most promising developments of research on hydraulic machines and devices concerns optimization of phenomena occurring in gaps, ultimately leading to prolonging the life and increasing the reliability of these machines. Awareness of gap oil parameters, including pressure distribution, is useful for the designers of hydraulic systems [6, 8, 9, 11, 13, 14, 17, 15, 18].

Generally, what is understood as a gap is an oilfilled space between two adjacent surfaces in hydraulic machines. The gap height, i.e. the distance between the surfaces, is usually about a few micrometers. Depending on the shape of the adjacent elements, gaps can also take different shapes.

One of the most typical kinds of gaps is a ring gap occurring, among others, between the piston and cylinder in a piston pump. A fundamental classification of ring



Fig. 1. Classification of ring gaps

gaps is presented in Fig. 1. A concentric gap, in which the piston axis coincides with the cylinder axis exist only in theory. In practice, the gap height varies along the cylinder due to such factors as weight, inaccuracy of manufacturing, or load asymmetry of the surfaces [16].

In this paper pressure distribution in conical gaps will be discussed. The oil may flow towards the narrower end of the gap, i.e. a confusor gap, or towards the wider end of the gap, i.e. a diffuser gap [19, 22].

All gaps, including ring ones, are a source of volumetric loss, and the leakage can occur due to pressure flow, resulting from the difference between the pressures at the gap ends, due to friction flow, resulting from the piston motion, or due to pressure-friction flow resulting from the motion of the piston and the pressure difference at the gap ends [10].

# APPLICATION OF THE NAVIER-STOKES EQUATIONS FOR DETERMINING PRESSURE DISTRIBUTION IN THE GAP

The fluid motion in a ring gap can be described by means of the Navier-Stokes equations, and the continuity equation expressed in terms of the cylindrical coordinate system r,  $\varphi$ , z [7, 12]:

$$\frac{\partial \mathbf{v}_{r}}{\partial t} + \mathbf{v}_{r} \frac{\partial \mathbf{v}_{r}}{\partial r} + \frac{\mathbf{v}_{\varphi}}{r} \frac{\partial \mathbf{v}_{r}}{\partial \varphi} + \mathbf{v}_{z} \frac{\partial \mathbf{v}_{r}}{\partial z} - \frac{\mathbf{v}_{\varphi}^{2}}{r} = \\ = F_{r} + \mathbf{v} \left( \frac{\partial^{2} \mathbf{v}_{r}}{\partial r^{2}} + \frac{1}{r} \frac{\partial \mathbf{v}_{r}}{\partial r} + \frac{1}{r^{2}} \frac{\partial^{2} \mathbf{v}_{r}}{\partial \varphi^{2}} + \frac{\partial^{2} \mathbf{v}_{r}}{\partial z^{2}} - \frac{\mathbf{v}_{r}}{r^{2}} - \frac{2}{r^{2}} \frac{\partial \mathbf{v}_{\varphi}}{\partial \varphi} \right) - \frac{1}{\rho} \frac{\partial p}{\partial r}, (1)$$

$$\frac{\partial v_{\varphi}}{\partial t} + v_{r} \frac{\partial v_{\varphi}}{\partial r} + \frac{v_{\varphi}}{r} \frac{\partial v_{\varphi}}{\partial \varphi} + v_{z} \frac{\partial v_{\varphi}}{\partial z} + \frac{2v_{r}v_{\varphi}}{r} =$$

$$= F_{\varphi} + v \left( \frac{\partial^{2} v_{\varphi}}{\partial r^{2}} + \frac{1}{r} \frac{\partial v_{\varphi}}{\partial r} + \frac{1}{r^{2}} \frac{\partial^{2} v_{\varphi}}{\partial \varphi^{2}} + \frac{\partial^{2} v_{\varphi}}{\partial z^{2}} + \frac{2}{r^{2}} \frac{\partial v_{r}}{\partial \varphi} - \frac{v_{\varphi}}{r^{2}} \right) - \frac{1}{\rho r} \frac{\partial p}{\partial \varphi}, (2)$$

2. .

au

$$\frac{\partial \mathbf{v}_{z}}{\partial t} + \mathbf{v}_{r} \frac{\partial \mathbf{v}_{z}}{\partial r} + \frac{\mathbf{v}_{\varphi}}{r} \frac{\partial \mathbf{v}_{z}}{\partial \varphi} + \mathbf{v}_{z} \frac{\partial \mathbf{v}_{z}}{\partial z} =$$
$$= F_{z} + \mathbf{v} \left( \frac{\partial^{2} \mathbf{v}_{z}}{\partial r^{2}} + \frac{1}{r} \frac{\partial \mathbf{v}_{z}}{\partial r} + \frac{1}{r^{2}} \frac{\partial^{2} \mathbf{v}_{z}}{\partial \varphi^{2}} + \frac{\partial^{2} \mathbf{v}_{z}}{\partial z^{2}} \right) - \frac{1}{\rho} \frac{\partial p}{\partial z}, \quad (3)$$

$$\frac{\partial \mathbf{V}_r}{\partial r} + \frac{1}{r} \frac{\partial \mathbf{V}_{\varphi}}{\partial \varphi} + \frac{\partial \mathbf{V}_z}{\partial z} + \frac{\mathbf{V}_r}{r} = 0.$$
(4)

The left sides of Equations  $(1 \div 3)$  represent the inertia forces of the working fluid and the right sides correspond to the forces of mass, viscosity, and pressure in oil [3, 20].

The ring gap presented in Fig. 2 is between a cylindrical piston and a conical cylinder. The piston axis is parallel to the cylinder axis and can be moved by the value of the eccentric e. Practically, the convergence angle  $\alpha$  is very small.

The value of the gap height was obtained from:

$$h = \frac{D_1 - d}{2} - e \cos \varphi + \frac{(D_2 - D_1)z}{2l}$$
(5)

where:

 $D_1$ ,  $D_2$  – the diameter of the cylinder orifice at the inlet and outlet of the gap, respectively,

- d the piston diameter,
- $\varphi$  the current angular position (0°  $\leq \varphi \leq$  360 °),
- z the current axial position ( $0 \le z \le l$ ).



Fig. 2. Confusor gap between the piston and the cylinder in an axial multi-piston pump

The piston moving inwards with the velocity  $v_p$  presses the oil out the cylinder chamber. At the same time, due to delivery pressure, the oil flows in the opposite direction to the piston (leakage  $Q_g$ ). At the gap inlet the pressure is  $p_1$  and at the outlet the pressure is  $p_2$ . The gap is of the confusor type if for any longitudinal section the gap height decreases in the direction of oil flow. A characteristic feature of conical gaps is the convergence, described as:

$$m = tg\alpha = \frac{h_2 - h_1}{l},\tag{6}$$

where:

 $h_1$ ,  $h_2$  – are the gap heights at the inlet and outlet, respectively, with the concentric position of the piston in the cylinder.

Additionally, the conical gap can be described by means of the convergence parameter k of the gap:

$$k = \frac{h_2 - h_1}{h_1}.$$
 (7)

The following assumptions were made concerning the fluid flow in the gap:

- the flow is laminar,
- the adjacent surfaces are rigid and do not bend,
- a gap of small height is completely filled with oil,
- tangent stress is Newtonian,
- the fluid is non-compressible with constant viscosity,
- liquid particles directly adjoining to the moving surfaces preserve the liquid velocity,

- inertia forces in the liquid are negligible.

The ratio of the backlash *h* to the piston radius *r* in the first and higher orders is also negligible  $(h/r = 0,0005 \div 0,003)$ . Besides, the velocity  $v_{\varphi}$  of the circumferential flow round the piston is also disregarded. Taking all these assumptions into consideration, the oil flow in the gap is treated as one-dimensional, and the system of equations  $(1 \div 4)$  is simplified [Nikitin 1982] and becomes:

2

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_z}{\partial r}\right) = \frac{1}{v\rho}\frac{\partial p}{\partial z},\tag{8}$$

$$\frac{\partial p}{\partial r} = 0, \tag{9}$$

$$\frac{1}{r}\frac{\partial \left(r\mathbf{v}_{r}\right)}{\partial r} + \frac{\partial \mathbf{v}_{z}}{\partial z} = 0.$$
 (10)

Let us introduce the dynamic viscosity coefficient  $\mu$ :

$$\mu = v\rho \,, \tag{11}$$

and solve the system of equations  $(8 \div 10)$ , and the formula for the pressure distribution in the conical gap is obtained:

$$p = p_{1} - \frac{\left(c+k\right)^{2} \cdot \left[2c \cdot \frac{z}{l} + k \cdot \left(\frac{z}{l}\right)^{2}\right]}{\left(2c+k\right) \cdot \left(c+k \cdot \frac{z}{l}\right)^{2}} \cdot \left(p_{1} - p_{2}\right) \pm \frac{6 \cdot \mu \cdot v_{p} \cdot l}{h_{1}^{2}} \cdot \frac{k \cdot \frac{z}{l} \cdot \left(\frac{z}{l} - 1\right)}{\left(2c+k\right) \cdot \left(c+k \cdot \frac{z}{l}\right)^{2}}, \quad (12)$$

where:

$$c = 1 - \frac{e}{h_1} \cos \varphi \,. \tag{13}$$

# RESULTS OF SIMULATIONS OF PRESSURE DISTRIBUTIONS IN CONICAL RING GAPS

Simulations of pressure distribution in conical ring gaps were conducted by means of software.

The following data were assumed for the sake of calculations:

- pressure at the gap inlet  $p_1 = 32$  [MPa],
- pressure at the gap outlet  $p_2 = 0$  [MPa],

$$-$$
 gap length  $l = 0,042$  [m],

- dynamic viscosity coefficient within the range from 0,0122 to 0,0616 [Pas],
- relative velocity of the piston from 0 to 6 [m/s].

Fig. 3 presents oil pressure distribution in a concentric conical gap depending on the gap convergence. In the confusor gap, the pressure grows along the gap (convex curves), and in the diffuser gap the pressure drops along the gap (concave curves). It can also be noted that for the cylindrical gap (m = 0) the pressure drop is linear.

Fig. 4 presents pressure distribution for friction flow of oil through the confusor gap. As can be seen, the influence of piston velocity on the pressure in the gap is significant.

Subsequently, the pressure-friction flow occurring in the majority of ring gaps in hydraulic systems will be discussed.

Fig. 5 presents oil pressure distribution in a concentric conical gap depending on the dynamic viscosity coefficient with the piston moving with the relative velocity of 2 m/s. In the confusor gap (Fig. 5a) the pressure grows together with the dynamic viscosity coefficient, whereas in the diffuser gap (Fig. 5b) the oil pressure decreases as the dynamic viscosity coefficient increases.

Fig. 6 presents pressure distribution in a concentric conical gap depending on the relative velocity of the piston. In the confusor gap (Fig. 6a) the pressure increases with the increase in the relative velocity of the piston, whereas in the diffuser gap (Fig. 6b) the pressure decreases as the relative velocity of the piston increases.

In concentric gaps the pressure around the piston is equal, however in the case of eccentric gaps it varies along the circumference. Fig. 7 presents the distribution of the circumferential pressure for the confusor and diffuser



Fig. 3. Pressure distribution in the concentric conical gap with pressure flow depending on the gap convergence direction



Fig. 4. Pressure distributions in the concentric confusor gap with friction flow, depending on the piston velocity



Fig. 5. Pressure distribution in a concentric conical gap depending on the dynamic viscosity coefficient for a) the confusor gap, b) the diffuser gap; with the piston relative velocity  $v_p = 2 \text{ m/s}$ 



Fig. 6. Pressure distribution in a concentric conical gap depending on the piston velocity for a) the confusor gap, b) the diffuser gap with the oil dynamic viscosity coefficient  $\mu$ = 0.0616 Pas



**Fig. 7.** Circumferential pressure distribution in an eccentric conical gap depending on the piston eccentric value with respect to the cylinder and on the circumferential angle for a) the confusor gap, b) the diffuser gap

gaps depending on the eccentric value e of the piston in the cylinder and the circumferential angle  $\varphi$ , with the dynamic viscosity coefficient equal to 0.0253 Pas. In the confusor gap the pressure relieving the piston towards its concentric position increases with the increase in the piston eccentric. In the diffuser gap the pressure under the piston decreases as the piston eccentric increases which leads to the undesirable effect of the piston clinging to cylinder.

#### CONCLUSIONS

The conducted study leads to the following conclusions:

- 1. The computational model adopted for the analyses is suitable for determining the pressure distribution in conical ring gaps.
- 2. In the confusor type ring gaps the pressure increases along the gap, whereas in the diffuser type ring gaps the pressure decreases.
- Pressure distribution in conical gaps depends to a significant extent on the gap convergence, oil viscosity and its eccentric position.

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# ROZKŁADY CIŚNIENIA OLEJU W SZCZELINACH PIERŚCIENIOWYCH STOŻKOWYCH

Streszczenie. W artykule przedstawiono problematykę związaną z przepływami oleju przez szczeliny pierścieniowe

występujące w tłokowych pompach i silnikach hydraulicznych. W oparciu o równania Naviera-Stokesa i równanie ciągłości wyznaczono zależność określającą ciśnienie panujące w szczelinie. Rezultaty obliczeń rozkładów ciśnienia w szczelinach konfuzorowych i dyfuzorowych przedstawiono w zależności od lepkości oleju i prędkości względnej tłoczka przy uwzględnieniu mimośrodowego jego położenia.

Słowa kluczowe: tłoczek-cylinder pompy, szczelina pierścieniowa, rozkłady ciśnienia.

# Pressure distributions in oil film in the front gap of a hydrostatic thrust bearing

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S u m m a r y. The paper presents pressure distributions in oil film in a front variable-height gap of a hydrostatic thrust bearing. On the basis of the Navier-Stokes equations and the continuity equation a formula was found describing the pressure in the gap. The influence was analyzed of geometrical dimensions and exploitation parameters of thrust bearings on circumferential pressure distribution near the smallest gap height. The numerical results of pressure values take into account the effects of oil viscosity, the smallest gap height, the inclination angle and angular velocity of the upper wall of the bearing, the pressure feeding the bearing and the ratio of the external to the internal bearing radius.

Key words: hydrostatic thrust bearing, pressure distributions, front gap.

#### INTRODUCTION

Hydrostatic thrust bearings support load distributed axially with respect to the shaft. Processes occurring in hydrostatic thrust bearings depend on the kind of gap. Typically, the front gap height is variable [13,20]. The gap shape can be confusor, diffuser or parallel and the pressure distribution varies accordingly (Fig.1) [9].



Fig. 1. Pressure distributions in the front gap: a) confusor, b) parallel, c) diffuser [9]

The operation of the valve plate - cylinder block system or of the slipper - swashplate system in an axial pump is analogous to the operation of a hydrostatic thrust bearing [6,7].

Complex phenomena occurring in gaps of hydrostatic bearings affect the efficiency of hydraulic machines [1,2,5,7,11,12,15,16,17,18,19] and devices and are therefore in the centre of interest of designers and development units.

Fig. 2 presents a general diagram of a hydrostatic thrust bearing with the front variable-height gap. The upper wall rotates with the angular velocity  $\omega$  around its axis and is typically inclined by the angle  $\varepsilon$  with respect to the lower wall. Oil flows out of the central chamber of the upper wall to the outside of the gap.



Fig. 2. Hydrostatic thrust bearing with a front variable-height gap

In a confusor gap an over- pressure peak occurs next to the smallest gap height whereas in a diffuser gap there is negative pressure limited by cavitation, which complicates the analytical description of the phenomenon. Cavitation also results in damages to the material in the form of crevasses [10].

# APPLICATION OF THE NAVIER-STOKES EQUATIONS FOR DETERMINING OIL PRESSURE DISTRIBUTIONS IN A FRONT GAP

Pressure changes in the front gap can be described on the basis of the Navier-Stokes equations and the flow continuity equation represented in the cylindrical coordinate system r,  $\varphi$ , z [3,4,8,14,21]:

$$\frac{\partial \mathbf{v}_{r}}{\partial t} + \mathbf{v}_{r} \frac{\partial \mathbf{v}_{r}}{\partial r} + \frac{\mathbf{v}_{\varphi}}{r} \frac{\partial \mathbf{v}_{r}}{\partial \varphi} + \mathbf{v}_{z} \frac{\partial \mathbf{v}_{r}}{\partial z} - \frac{\mathbf{v}_{\varphi}^{2}}{r} = \\ = \mathbf{v} \left( \frac{\partial^{2} \mathbf{v}_{r}}{\partial r^{2}} + \frac{1}{r} \frac{\partial \mathbf{v}_{r}}{\partial r} + \frac{1}{r^{2}} \frac{\partial^{2} \mathbf{v}_{r}}{\partial \varphi^{2}} + \frac{\partial^{2} \mathbf{v}_{r}}{\partial z^{2}} - \frac{\mathbf{v}_{r}}{r^{2}} - \frac{2}{r^{2}} \frac{\partial \mathbf{v}_{\varphi}}{\partial \varphi} \right) - \frac{1}{\rho} \frac{\partial p}{\partial r}, (1)$$

$$\frac{\partial \mathbf{v}_{\varphi}}{\partial t} + \mathbf{v}_{r} \frac{\partial \mathbf{v}_{\varphi}}{\partial r} + \frac{\mathbf{v}_{\varphi}}{r} \frac{\partial \mathbf{v}_{\varphi}}{\partial \varphi} + \mathbf{v}_{z} \frac{\partial \mathbf{v}_{\varphi}}{\partial z} + \frac{2\mathbf{v}_{r} \mathbf{v}_{\varphi}}{r} = \\ = \mathbf{v} \left( \frac{\partial^{2} \mathbf{v}_{\varphi}}{\partial r^{2}} + \frac{1}{r} \frac{\partial \mathbf{v}_{\varphi}}{\partial r} + \frac{1}{r^{2}} \frac{\partial^{2} \mathbf{v}_{\varphi}}{\partial \varphi^{2}} + \frac{\partial^{2} \mathbf{v}_{\varphi}}{\partial z^{2}} + \frac{2}{r^{2}} \frac{\partial \mathbf{v}_{r}}{\partial \varphi} - \frac{\mathbf{v}_{\varphi}}{r^{2}} \right) - \frac{1}{\rho r} \frac{\partial p}{\partial \varphi}, (2)$$

$$\frac{\partial \mathbf{v}_{z}}{\partial t} + \mathbf{v}_{r} \frac{\partial \mathbf{v}_{z}}{\partial r} + \frac{\mathbf{v}_{\varphi}}{r} \frac{\partial \mathbf{v}_{z}}{\partial \varphi} + \mathbf{v}_{z} \frac{\partial \mathbf{v}_{z}}{\partial z} = \\ = \mathbf{v} \left( \frac{\partial^{2} \mathbf{v}_{z}}{\partial r^{2}} + \frac{1}{r} \frac{\partial \mathbf{v}_{z}}{\partial r} + \frac{1}{r^{2}} \frac{\partial^{2} \mathbf{v}_{z}}{\partial \varphi^{2}} + \frac{\partial^{2} \mathbf{v}_{z}}{\partial z^{2}} \right) - \frac{1}{\rho} \frac{\partial p}{\partial z}, \quad (3)$$

$$\frac{\partial \mathbf{v}_r}{\partial r} + \frac{1}{r} \frac{\partial \mathbf{v}_{\varphi}}{\partial \varphi} + \frac{\partial \mathbf{v}_z}{\partial z} + \frac{\mathbf{v}_r}{r} = 0.$$
(4)

It was assumed that oil is incompressible, the flow is laminar and isothermal, liquid motion is steady and uniform. The gap is completely filled with oil and tangent stress is Newtonian. Liquid particles directly adjacent to the moving surface retain their velocity. Besides, the surfaces limiting the gap are rigid and inertia forces are negligible. If  $v_r = v_r(r, z)$  and  $v_z = 0$ , Eqs. (1 ÷ 4) become:

$$0 = v \frac{\partial^2 v_r}{\partial z^2} - \frac{1}{\rho} \frac{\partial p}{\partial r},$$
(5)

$$\mathbf{0} = \frac{\partial^2 \mathbf{v}_{\varphi}}{\partial z^2},\tag{6}$$

$$0 = \frac{\partial p}{\partial z},\tag{7}$$

$$0 = \frac{\partial \mathbf{v}_r}{\partial r} + \frac{1}{r} \frac{\partial \mathbf{v}_{\varphi}}{\partial \varphi} + \frac{\mathbf{v}_r}{r}.$$
(8)

Introducing the dynamic viscosity coefficient  $\mu = v\rho$  turns Eq. (5) into

$$\frac{\partial^2 \mathbf{v}_r}{\partial z^2} = \frac{1}{\mu} \frac{\partial p}{\partial r}.$$
(9)

After double integrating Eq. (9) becomes:

$$\mathbf{v}_r = \frac{1}{2\mu} \frac{\partial p}{\partial r} z^2 + C_1 z + C_2. \tag{10}$$

The integration constants  $C_1$  and  $C_2$  are determined on the basis of the following boundary conditions:

for z = 0,  $v_r = 0$  and for z = h,  $v_r = 0$ ,

The integration constants are, respectively:

$$C_1 = -\frac{1}{2\mu} \frac{\partial p}{\partial r} h, \tag{11}$$

$$C_2 = 0.$$
 (12)

Substituting (11) and (12) into Eq. (10):

$$\mathbf{v}_r = \frac{1}{2\mu} \frac{\partial p}{\partial r} \Big( z^2 - hz \Big). \tag{13}$$

After integrating Eq. (6) twice with respect to the variable z:

$$v_{\varphi} = C_3 z + C_4.$$
 (14)

The integration constants  $C_3$  and  $C_4$  are obtained on the basis of the following boundary conditions

for z = 0,  $v_{\omega} = 0$  and for z = h,  $v_{\omega} = \omega \cdot r$ ,

The integrations constants are, respectively:

$$C_3 = \frac{\omega r}{h},\tag{15}$$

$$C_4 = 0.$$
 (16)

Substituting the constants  $C_3$  and  $C_4$  into Eq. (14) leads to:

$$\mathbf{v}_{\varphi} = \frac{\omega r}{h} z. \tag{17}$$

When (13) and (17) are taken into account, Eq. (8) becomes:

$$0 = \frac{1}{2\mu} \frac{\partial^2 p}{\partial r^2} \left( z^2 - hz \right) - \omega z \frac{1}{h^2} \frac{dh}{d\varphi} + \frac{1}{2\mu r} \frac{\partial p}{\partial r} \left( z^2 - hz \right).$$
(18)

After integrating Eq. (18) with respect to the variable z within the limits from 0 to h and with subsequent transformations:

$$\frac{\partial}{\partial r} \left( r \frac{\partial p}{\partial r} \right) = -6\mu\omega r \frac{1}{h^3} \frac{dh}{d\varphi}.$$
 (19)

Then, integrating Eq. (19) twice with respect to the variable r

$$p = -\frac{3}{2}\mu\omega r^{2}\frac{1}{h^{3}}\frac{dh}{d\varphi} + C_{5}\ln r + C_{6}$$
(20)

The integration constants  $C_5$  and  $C_6$  are obtained on the basis of the following boundary conditions

for 
$$\mathbf{r} = \mathbf{r}_1$$
,  $\mathbf{p} = \mathbf{p}_1$  and for  $\mathbf{r} = \mathbf{r}_2$ ,  $\mathbf{p} = \mathbf{p}_2 = 0$ 

The integration constants are, respectively

$$C_{5} = \frac{3}{2} \mu \omega \frac{1}{\ln \frac{r_{2}}{r_{1}}} \frac{1}{h^{3}} \frac{dh}{d\varphi} \left(r_{2}^{2} - r_{1}^{2}\right) - \frac{p_{1}}{\ln \frac{r_{2}}{r_{1}}}$$
(21)

$$C_{6} = \frac{3}{2}\mu\omega r_{2}^{2} \frac{1}{h^{3}} \frac{dh}{d\varphi} - \frac{3}{2}\mu\omega \frac{\ln r_{2}}{\ln \frac{r_{2}}{r_{1}}} \frac{1}{h^{3}} \frac{dh}{d\varphi} \left(r_{2}^{2} - r_{1}^{2}\right) + \frac{p_{1}\ln r_{2}}{\ln \frac{r_{2}}{r_{1}}}$$
(22)

Substituting the integration constants  $C_5$  and  $C_6$  to Eq. (20) leads to the following formula for the pressure p in the front gap

$$p = \frac{3}{2}\mu\omega \frac{1}{\ln\frac{r_2}{r_1}} \frac{1}{h^3} \frac{dh}{d\varphi} \left[ \left( r_2^2 - r^2 \right) \ln\frac{r_2}{r_1} - \left( r_2^2 - r_1^2 \right) \ln\frac{r_2}{r} \right] + p_1 \frac{\ln\frac{r_2}{r}}{\ln\frac{r_2}{r_1}}$$
(23)

# RESULTS OF SIMULATION EXPERIMENTS ON PRESURE DISTRIBUTION NEXT TO THE SMALLEST HEIGHT OF THE FRONT GAP

The simulation experiments were carried out by means of software. The gap height was obtained from [22]

 $h = -r\sin\varphi\cos\delta\tan\varepsilon - r\cos\varphi\sin\delta\tan\varepsilon + r_2\tan\varepsilon + h_1$ (24)

The following parameters were assumed in the computations:

- pressure at the gap entrance  $p_1 = 20$  [MPa],
- pressure at the gap exit  $p_2 = 0$  [MPa],
- bearing internal radius  $r_1 = 0.004$  [m] and bearing external radius  $r_2 = 0.012$  [m],
- dynamic viscosity coefficient μ within the range 0.0122
   0.0616 [Pas],
- angular velocity  $\omega$  of the upper wall within the range 100 200 [rad/s],
- inclination angle  $\varepsilon$  of the upper wall within the range 0.01 0.03 [°],
- angle  $\delta = 45$  [°] of the smallest gap height  $h_1$  with respect to the axis x.

Fig. 3 presents the circumferential pressure distribution on the radius r = 0.011 [m] next to the smallest front gap height. As the smallest gap is approached along the circumference in a confusor gap, an over-pressure peak is encountered. At the other side, when moving away from the smallest gap a negative pressure occurs, limited by cavitation.



**Fig. 3.** Distribution of circumferential oil pressure next to the smallest gap height on the radius r = 0.011 [m] ( $\varepsilon = 0.02$  [°],  $h_1 = 0.5$  [µm],  $\mu = 0.0253$  [Pas],  $\omega = 150$  [rad/s],  $p_1 = 20$  [MPa],  $r_2/r_1 = 3$ )

Fig. 4 presents oil pressure distributions in a confusor gap of a thrust bearing depending on the inclination angle of the upper wall. As the angle decreases, the maximum pressure increases.



**Fig. 4.** Distributions of circumferential oil pressure on the radius r = 0.011 [m] in a confusor gap depending on the angle  $\varepsilon$  of the upper wall inclination ( $h_1 = 0.5$  [µm],  $\mu = 0.0253$  [Pas],  $\omega = 150$  [rad/s],  $p_1 = 20$  [MPa],  $r_2r_1 = 3$ )

Fig. 5 presents oil pressure distributions in a confusor gap of a thrust bearing depending on the smallest gap height. Similarly as above, as the minimum gap height decreases, the maximum pressure increases.



**Fig. 5.** Oil pressure distributions on the radius r = 0.011 [m] in a front confusor gap depending on the smallest gap height  $h_1$  ( $\varepsilon = 0.02$  [°], $\mu = 0.0253$  [Pas], $\omega = 150$  [rad/s], $p_1 = 20$  [MPa], $r_2r_1 = 3$ )

Fig. 6 shows oil pressure distributions in a confusor gap of a thrust bearing depending on oil viscosity. With increase in oil viscosity, the maximum pressure also increases.



**Fig. 6.** Distributions of circumferential oil pressure on the radius r = 0.011 [m] in a front confusor gap depending on the oil viscosity coefficient  $\mu$  ( $\varepsilon = 0.02$  [°],  $h_1 = 0.5$  [ $\mu$ m],  $\omega = 150$  [rad/s],  $p_1 = 20$  [MPa],  $r_2r_1 = 3$ )

In Fig. 7 oil pressure distributions can be seen in a confusor gap of a thrust bearing depending on the angular velocity of the bearing upper wall. As the angular velocity increases, the maximum pressure increases too.



**Fig. 7.** Distributions of circumferential oil pressure on the radius r = 0.011 [m] in a front confusor gap depending on the angular velocity  $\omega$  of the upper wall ( $\varepsilon = 0.02$  [°],  $h_1 = 0.5$  [µm],  $\mu = 0.0253$  [Pas],  $p_1 = 20$  [MPa],  $r_2r_1 = 3$ )

Fig. 8 presents oil pressure distributions in a confusor gap of a thrust bearing depending on the pressure feeding the bearing. It can be observed that the influence of the feeding pressure on the maximum pressure value is small.



**Fig. 8.** Distributions of circumferential oil pressure on the radius r = 0.011 [m] in a front confusor gap depending on the feeding pressure  $p_1$  of a thrust bearing ( $\varepsilon = 0.02$  [°],  $h_1 = 0.5$  [µm],  $\mu = 0.0253$  [Pas],  $\omega = 150$  [rad/s],  $r_2r_1 = 3$ )

Fig. 9 shows distributions of oil hyper-pressure in a confusor gap of a thrust bearing depending on the ratio of the external to internal bearing radius. As the ratio increases, the maximum pressure in the gap also increases.



**Fig. 9.** Distributions of circumferential oil pressure on the radius r = 0.011 [m] in a front confusor gap depending on the bearing dimensions ( $\varepsilon = 0.02$  [°],  $h_1 = 0.5$  [µm],  $\mu = 0.0253$  [Pas],  $\omega = 150$  [rad/s],  $p_1 = 20$  [MPa])

#### CONCLUSIONS

The study leads to the following conclusions:

- 1. The computation model adopted in this paper enables determining pressure distributions in front gaps of hydrostatic thrust bearings.
- 2. The occurrence of pressure peaks in a front confusor gap depends on a number of geometrical and exploitation parameters of the thrust bearing.
- 3. A local increase of pressure in a front confusor gap can contribute to additional relief of the hydrostatic thrust bearing, whereas a pressure drop in a front diffuser gap is disadvantageous, since it causes cavitation and, consequently, material damage.

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# ROZKŁADY CIŚNIENIA W FILMIE OLEJOWYM SZCZELINY CZOŁOWEJ ŁOŻYSKA HYDROSTATYCZNEGO WZDŁUŻNEGO

S treszczenie. W artykule przedstawiono rozkłady ciśnienia w filmie olejowym szczeliny czołowej o zmiennej wysokości w łożysku hydrostatycznym wzdłużnym. W oparciu o równania Naviera-Stokesa i równanie ciągłości wyznaczono zależność określającą ciśnienie panujące w szczelinie. W pracy analizowano wpływ parametrów geometryczno-eksploatacyjnych łożysk wzdłużnych na rozkłady ciśnienia obwodowego w otoczeniu najmniejszej wysokości szczeliny. Przedstawiono rezultaty obliczeń wartości ciśnienia z uwzględnieniem wpływu lepkości oleju, najmniejszej wysokości szczeliny, kąta pochylenia i prędkości kątowej górnej ścianki łożyska, ciśnienia zasilającego łożysko oraz ilorazu promienia zewnętrznego i wewnętrznego łożyska.

Słowa kluczowe: łożysko hydrostatyczne wzdłużne, rozkłady ciśnienia, szczelina czołowa.

# Impact of exploitation parameters on the hydrostatic relief of the cylinder block in an axial piston pump

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S u m m a r y. The paper presents results of numerical analysis of the variable overpressure-peak induced hydrostatic relief force operating on the cylinder block in axial piston pumps. The hydrostatic relief force of the cylinder block was obtained from the pressure distribution on the valve plate in a variable height gap by means of the numerical Gauss cubature method. The analysis of the overpressure-peak induced hydrostatic relief force was performed as a function of the angular velocity of the cylinder block and of the dynamic viscosity coefficient of oil.

Key words: Hydrostatic relief force of the cylinder block, variable-height gap, piston pump.

#### INTRODUCTION

Multi-piston pumps are applied in a number of industry branches. They operate with high pressures and high powers and are therefore characterized by high power efficiency coefficients, defined as the ratio of power to mass or volume. Because of that such pumps are mostly used in devices which require highly efficient and effective drives [9,14,16,17,18]. When an axial multi-piston pump is operating there appears a small gap between the cylinder block and the valve plate. The gap is filled with oil and due to the slanting position of the cylinder block, the gap height becomes variable (Fig. 1) [4,5,10,11].

The studies of hydrostatic pressure distribution in a variable-height gap have shown that an overpressure peak appears there [6,22].

The paper employs the numerical method of determining the hydrostatic relief force of the cylinder block taking into consideration the overpressure peak occurring in the gap at its lowest height.

# PRESSURE DISTRIBUTION OF OIL FILM IN A VARIABLE-HEIGHT GAP AND THE REYNOLDS EQUATION

The pressure distribution of oil film in a variableheight gap on the valve plate in an axial multi-piston



Fig. 1. Regular position of the cylinder block with respect to the valve plate

pump can be described by means of the Reynolds equation (1) [14,12,3]:

$$\frac{\partial}{\partial x} \left( \frac{h^3 \rho}{\eta} \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{h^3 \rho}{\eta} \frac{\partial p}{\partial y} \right) = \\ = 6 \frac{\partial}{\partial x} (\rho u h) + 6 \frac{\partial}{\partial y} (\rho v h) + 12 \rho w, \qquad (1)$$

where: p – the pressure in the gap, h – the gap height,  $\rho$  – the working fluid density,  $\eta$  – the dynamic viscosity coefficient, u,v,w – the components of rotational velocity by the prescribed angular velocity  $\omega$  and the radius vector r of the cylinder block with respect to the directions of the coordinate axes x, y, z.

The solution of the Reynolds equation (1) is valid if the following assumptions are met:

- the flow in the front gap is laminar,
- fluid friction occurs between the adjacent surfaces,
- the lubricant is an incompressible Newtonian fluid,
- the pressure is constant in the direction orthogonal to the surface,
- the adjacent surfaces are rigid.

The task of solving equation (1) analytically is quite complicated, particularly for surfaces of more complex shape. Therefore, the equation was solved numerically using the finite element method, integrated into the computer programme Reynolds developed by the authors of the present paper. The programme offers the possibility of examining the pressure distribution in a variable-height gap on the valve plate, for varying geometrical and exploitation parameters, such as the inclination angle of the cylinder block, its angular velocity, the dynamic viscosity coefficient and the minimal gap height. The programme makes it possible to read input data and to save results in files compatible with the software NuscaS [15].

The programme operates in the following stages:

- reading the finite elements mesh for the valve plate (Fig.2),
- assembling the system of equations [8,20],
- determining the boundary conditions,
- solving the system of equations [2,13],



Fig. 2. Computational domain of the valve plate and part of the finite element mesh

- saving the results.

The main advantages of the programme are applying such data structures, which do not burden the operational memory with zero elements of sparse matrices in the system of equations and applying the Conjugate Gradient method with Jacobi preconditioning [1] for solving the equations, which significantly fosters the convergence of results.

The examination of the oil film pressure distribution in a variable-height gap on the valve plate proved the existence of overpressure peaks next to the smallest gap height. Fig. 3 presents an example of pressure distribution on the valve plate and the graph representing the variation of oil film pressure next to the smallest gap height at the radius r = 0.0366 m. The pressure distribution was examined for the minimal gap heigh  $h_1 = 0.3 \times 10^{-6}$  m, the angular velocity of the cylinder block  $\omega = 157$  rad/s, the dynamic viscosity coefficient of oil  $\eta = 0.0253$  Pas and the angle  $\delta = 0.785$  rad of the position of the minimal gap height  $h_1$  with respect to the axis x. The characteristic radiuses of the valve plate are  $r_1 = 0.0284$  m,  $r_2 = 0.0304$ m,  $r_3 = 0.0356$  m and  $r_4 = 0.0376$  m, respectively.

# OBTAINING THE HYDROSTATIC RELIEF FORCE OF THE CYLINDER BLOCK

On the basis of the software Reynolds for calculating pressure distribution on the valve plate, a method was developed for obtaining the hydrostatic relief force, based on the numerical Gauss cubature method [7].

In this method each of the triangular finite elements of the mesh is brought to a standardized right-angled triangle with the nodes (0,0), (1,0) and (0,1) (Fig.4).

The coordinates of the finite element can be obtained in the following way from the standardized triangle:

$$\mathbf{x} = \mathbf{x}_{1} + (\mathbf{x}_{2} - \mathbf{x}_{1})\zeta + (\mathbf{x}_{3} - \mathbf{x}_{1})\gamma,$$
(2)

$$y = y_1 + (y_2 - y_1)\zeta + (y_3 - y_1)\gamma,$$
(3)



where:  
(x1,y1) 
$$\rightarrow$$
 (0,0); (x2,y2)  $\rightarrow$  (1,0); (x3,y3)  $\rightarrow$  (0,1).

During the standardization the system of coordinates is changed and it is necessary to calculate the Jacobian of the transformation. In the case of triangular elements it is:

$$|J| = \begin{vmatrix} \frac{\partial x}{\partial \zeta} & \frac{\partial x}{\partial \gamma} \\ \frac{\partial y}{\partial \zeta} & \frac{\partial y}{\partial \gamma} \end{vmatrix} = \begin{vmatrix} (x_2 - x_1) & (x_3 - x_1) \\ (y_2 - y_1) & (y_3 - y_1) \end{vmatrix} = 2|D|, (4)$$

where:

D - the area of a triangular element.

The value of pressure for the standardized element can be obtained from:

$$p(\zeta, \gamma) = |J| p(x, y), \tag{5}$$

where:

p(x,y) – the interpolated value of pressure obtained from the nodal values of the finite triangular element and the shape function [21].

The ultimate formula for the relief force from a triangular finite element is:

$$F_{ele} = \int_{0}^{1} d\zeta \int_{0}^{1-\gamma} p(\zeta,\gamma) d\gamma = \frac{1}{2} \sum_{i=1}^{n} p(\zeta_{i},\gamma_{i}) w_{i}, \quad (6)$$

where:

 $\zeta_{i'}\gamma_i$  – the Gaussian coordinates,  $w_i$  – the weighs of the Gaussian points, n – the number of the Gaussian points.

The overpressure-peak induced hydrostatic relief force occurring in the neighborhood of the smallest gap height was calculated according to the algorithm below (Fig. 5).

# **RESULTS OF COMPUTATIONS**

The method described above was used for analyzing the overpressure peak-induced hydrostatic relief force of the cylinder block as a function of the angular velocity  $\omega$  of the cylinder block and the dynamic viscosity coefficient  $\eta$  of oil.

The following input parameters were assumed in the analysis:

- in the pressure port the pressure  $p_{t} = 32$  MPa,

- in the suction port the pressure  $p_s = 0.1$  MPa,



Fig. 3. Oil film pressure distribution on the valve plate and pressure variation next to the smallest gap height as a function of the rotation angle of the cylinder block



Fig. 4. Transformation of the finite triangular element to the standardized right-angled triangle



Fig. 5. Algorithm for calculating the overpressure-peak induced hydrostatic relief force occurring on the valve plate of the multipiston axial pump

- outside and inside the valve plate the pressure  $p_0 = 0$  MPa,
- the angular velocity of the cylinder block  $\omega = 157$  rad/s
- the dynamic viscosity of the oil  $\mu = 0.0253$  Pas,
- the angle of the smallest height of the gap with respect to the axis x  $\delta = 0.785$  rad,
- the inclination angle of the cylinder block with respect of the valve plate  $\varepsilon = 0.000523$  rad,
- the minimal gap height  $h_1 = 0.3 \times 10^{-6}$  m
- the characteristic radiuses of the valve plate are  $r_1$ = 0.0284 m,  $r_2$  = 0.0304 m,  $r_3$  = 0.0356 m, and  $r_4$  = 0.0376 m.

Fig. 6 presents the variation in the overpressure-peak induced hydrostatic relief force depending on the variable angular velocity  $\omega$  of the cylinder block. It follows from the analysis that an increase in the angular velocity causes an increase in the value of the hydrostatic relief force, with the increasing overpressure peak and with the constant smallest gap height. In practice, however, an increase in the hydrostatic relief force is accompanied by an increase in the gap height, and consequently, decay of the overpressure peak.

Fig. 7 presents a change in the overpressure-peak induced hydrostatic relief force depending on the variable dynamic viscosity coefficient  $\eta$  of oil. As can be noted,



Fig. 6. Overpressure-peak induced hydrostatic relief force as a function of the angular velocity  $\omega$  of the cylinder block
an increase in the dynamic viscosity coefficient causes an increase in the overpressure-peak induced hydrostatic relief force with the constant smallest gap height.



Fig. 7. Overpressure-peak induced hydrostatic relief force of the cylinder block as a function of the dynamic viscosity coefficient  $\eta$  of oil

The simulation experiments show that for the increase in the angular velocity of the cylinder block from 52 to 261 rad/s, the percentage rate of the overpressure-peak induced hydrostatic relief force to the hydrostatic relief force of the cylinder block ranges from 1.25 to 6.49 %. The increase in the oil viscosity from 0.01 to 0.05 Pas causes a relative increase in the overpressure-peak induced hydrostatic relief force with respect to the relief of the cylinder block ranging from 1.59 to 7.57 % with the constant minimal gap height of  $h_1 = 0.3 \times 10^{-6}$  m.

#### CONCLUSIONS

The study leads to the following conclusions:

- 1. The computational model developed makes it possible to determine the hydrostatic relief force of the cylinder block.
- 2. Increases in the angular velocity of the cylinder block and in oil viscosity cause increase in the overpressure peak and at the same time increase in the hydrostatic force relieving the cylinder block with the constant minimal height of the gap.
- 3. In the actual exploitation of hydraulic machines, increase in the overpressure-peak induced hydrostatic relief force causes increase in the minimal gap height and at the same time decreases the overpressure peak, which again decreases the hydrostatic relief force.

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WPŁYW PARAMETRÓW EKSPLOATACYJNYCH NA ODCIĄŻENIE HYDROSTATYCZNE BLOKU CYLINDROWEGO POMPY WIELOTŁOCZKOWEJ

Streszczenie. W pracy przedstawiono wyniki analizy numerycznej siły zmiennego odciążenia hydrostatycznego bloku cylindrowego pompy wielotłoczkowej osiowej wynikającej z powstającego piku nadciśnienia. Siłę odciążenia hydrostatycznego bloku cylindrowego wyznaczano z rozkładu ciśnienia na tarczy rozdzielacza w szczelinie o zmiennej wysokości wykorzystując metodę numeryczną kubatur Gaussa. Analizę siły hydrostatycznej odciążającej pochodzącej od piku nadciśnienia przeprowadzono w zależności od prędkości kątowej bloku cylindrowego i współczynnika lepkości dynamicznej oleju.

Słowa kluczowe: siła odciążenia hydrostatycznego bloku cylindrowego, szczelina o zmiennej wysokości, pompa tłokowa.

# Load of the kinematic pair piston-cylinder block in an axial piston pump

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Summary. The paper presents an analysis of the load of the kinematic pair piston-cylinder block in an axial piston pump. The analysis was carried out by means of a spatial models of discrete and analog piston load. The value of reaction and friction forces occurring between the piston and cylinder block were determined for a typical axial piston pump. The load simulation was performed by means of the Mathcad software [15].

Key words: axial piston pump, piston load.

# INTRODUCTION

Axial piston pumps have numerous industrial applications due to their ability to work with high pressures and high powers, as well as high efficiency understood as a ratio of power to mass or volume [11,12,20]. This type of displacement machines is most often employed in the drives of complex machines with high efficiency requirements [19,24]. This motivates continuous research on how to further improve exploitation parameters and modernize construction of these pumps. The most important applications of hydraulic piston pumps include products of the companies Parker, Bosch-Rexroth and others, mostly in the following fields:

- aviation industry (airplanes),
- automotive industry (presses, numerical control machine tools, injection molding machines),
- heavy industry (pressure foundries, rolling mills, cokeries),
- building industry (excavators, loaders, extension arms),
- agriculture and forestry machines (forest cranes, elevators, drill rigs, mowers, combine-harvesters),
- military roadway systems (multifunction vehicles, building bridges).

One of the most popular types of piston machines with axial pistons are axial piston pumps with a sloping swash plate (Fig. 1) [1,3,5,7,10,14,16,17,18,22]. The cylinder block 4 rotates with the pistons 2, and the valve plate 9 and the swash plate 5 are stationary. By varying the inclination angle of the swash plate, the path of the



Fig. 1. The main elements of the axial piston pump: 1 - shaft, 2 - piston, 3 - slipper, 4 - cylinder block, 5 - swash plate, 6 - retainer plate, 7 - central spring, 8 - valve plate of the cylinder block, 9 - valve plate [11]

pistons is affected in their to-and fro motion and at the same time the flow intensity of the operating liquid varies.

Energy losses in axial piston pumps are most often caused by the operation of the kinematic pair pistoncylinder block.

# ANALYSIS OF PISTON LOAD BY MEANS OF THE DISCRETE AND ANALOG MODELS

One of the characteristic features of the operation of the piston-cylinder block system in axial piston pumps with a sloping swash plate is that the hydrostatic slipper is acted upon by the radial force originating from pressure force. (Fig. 2).



Fig. 2. Forces in the piston system represented on a plane [6]

The radial force  $F_R$ , by pressing the piston towards the cylinder, causes that the piston's position is not parallel to the cylinder and strong reactions  $R_A$  i  $R_B$  appear [11]. As a result, the friction force  $F_T$  occurs in the piston working cycle. The friction force  $F_T$  can be obtained from [6,13,20]:

$$F_{T} = \mu (R_{A} + R_{B}). \tag{1}$$

In the available literature, the computations of reaction forces were performed in a two-dimensional system for an extreme case, i.e. for the maximum piston displacement.

In this paper, a spatial model is employed for obtaining the reactions  $R_A$  and  $R_B$  as functions of the angle  $\varphi$ of the cylinder block rotation. Typically, two cases of the piston system load are considered: the discrete model [6], assuming a focused load and the analog model [19, 22], assuming a continuous load in a two-dimension system. Fig. 3 shows the discrete model of the piston system load in the three-dimensional representation. It was assumed in the model that the following forces operate: the pressure force  $F_n$  originating from the pressure, the dynamic force  $F_{a}$  resulting from the changes in the piston system velocity in the to-and-fro motion, the inertia force  $F_{a}$ occurring due to the rotation of the piston system around the axis, the spring force  $F_{\rm spr}$  pressing the piston system to the swash plate, the force  $F_{st}$  of the hydrostatic relief of the slipper, the friction forces between the piston and the cylinder block  $\mu R_A$  and  $\mu R_B$ , and the friction force  $F_{TS}$ between the slipper and the swash plate.  $R_{A}$  and  $R_{B}$  are reactions acting where the piston presses on the sleeve inside the cylinder block and reaction  $R_s$  is exerted by the slipper toward the swash plate.

On the basis of the distribution of forces, as shown in Fig. 3, 3 equations are formulated representing projections of the forces onto the X, Y and Z axes and 2 equations representing moments with respect to the X and Y, axes. All these equation are presented in a general form as:

$$\sum F_{iX} = 0, \sum F_{iY} = 0, \sum F_{iZ} = 0, \sum M_{iX} = 0 \text{ i } \sum M_{iY} = 0.$$
(2)

There are 5 equations and 5 unknowns:  $R_{AX}$ ,  $R_{AY}$ ,  $R_{BX}$ ,  $R_{BY}$  and  $R_s$ . The equations were solved by means of the Cramer method [2].

Active forces occurring in the model were obtained from the formulas:



Fig. 3. Piston load in the discrete model

$$F_p = p_t \cdot \frac{\pi \cdot d^2}{4},\tag{3}$$

$$F_{st} = C \cdot \frac{p_t \cdot \pi}{2} \cdot \left( \frac{r_{zs}^2 - r_{ws}^2}{\ln \frac{r_{zs}}{r_{ws}}} \right), \tag{4}$$

$$F_{a_i} = m_c \cdot \omega^2 \cdot r_p \cdot \mathrm{tg}\alpha \cdot \cos\varphi_i, \tag{5}$$

$$F_{\omega} = m_c \cdot \omega^2 \cdot r_p. \tag{6}$$

According to the Cramer method [2] the following set of equations was assumed:

$$A \cdot R_{AY} + B \cdot R_{AX} + C_i \cdot R_s = J_i ,$$
  

$$D_i \cdot R_{AY} + E_i \cdot R_{AX} + F_i \cdot R_s = K_i ,$$
  

$$G_i \cdot R_{AY} + H_i \cdot R_{AX} + I_i \cdot R_s = L_i .$$
(7)

The angular range  $\psi$  of the main pressure zone is treated as constant. The zone takes the range from  $\frac{\alpha_m - \alpha_c}{2}$  to  $\pi$  (the point of departure of the cylinder block for the overlap of the valve plate) with the constant pressure  $p_r$ .

The set of equations (7) was solved by means of the Cramer formulas [2], utilizing the following expressions:

$$R_{AY_i} = \frac{R_{AY1_i}}{R_i},\tag{8}$$

$$R_{AX_i} = \frac{R_{AXI_i}}{R_i},\tag{9}$$

$$R_{S_i} = \frac{R_{S1_i}}{R_i},$$
 (10)

where

$$R_i = \begin{vmatrix} A & B & C_i \\ D_i & E_i & F_i \\ G_i & H_i & I_i \end{vmatrix},$$
(11)

$$R_{AY1_{i}} = \begin{vmatrix} J_{i} & B & C_{i} \\ K_{i} & E_{i} & F_{i} \\ L_{i} & H_{i} & I_{i} \end{vmatrix},$$
(12)

$$R_{AX1_{i}} = \begin{vmatrix} A & J_{i} & C_{i} \\ D_{i} & K_{i} & F_{i} \\ G_{i} & L_{i} & I_{i} \end{vmatrix},$$
(13)
$$R_{S1_{i}} = \begin{vmatrix} A & B & J_{i} \\ D_{i} & E_{i} & K_{i} \\ G_{i} & H_{i} & L_{i} \end{vmatrix},$$
(14)

The total reactions are:

$$R_{A_i} = \sqrt{R_{AX_i}^2 + R_{AY_i}^2}, \qquad (15)$$

$$R_{B_i} = \sqrt{R_{BX_i}^2 + R_{BY_i}^2}.$$
 (16)

In the computation model it was also assumed that the pressure variation in the upper transition zone between the suction zone and the pressure zone is linear [4] in the angular range from 0 to  $\frac{\alpha_m - \alpha_c}{2}$  i.e. from 0° to 9,283° in accordance with:

$$p_{j} = p_{s} + \frac{2 \cdot (p_{t} - p_{s})}{\alpha_{m} - \alpha_{c}} \cdot \varphi_{j}.$$
(17)

The hydrostatic force acting on the piston surface varies in accordance with:

$$F_{pj} = p_j \cdot \frac{\pi \cdot d^2}{4}.$$
 (18)

Also, the hydrostatic relief force of the slipper varies, as below:

$$F_{stj} = C \cdot \frac{p_j \cdot \pi}{2} \cdot \left( \frac{r_{zs}^2 - r_{ws}^2}{\ln \frac{r_{zs}}{r_{ws}}} \right). \tag{19}$$

Introducing the analog model of the load of the kinematic pair piston-cylinder made it possible to calculate the load of the pair also in the spatial system. Fig. 4 shows the computation model of the analog load.

Unlike in the previously discussed model, a triangular distribution of the analog load occurring between the piston and cylinder was assumed, as discussed in [8,19,20].

In the analog model a coefficient of load transformation k was introduced (Fig. 4). The coefficient was obtained by solving Eq. (20) and taking into account the reactions  $R_A$  and  $R_B$  of the discrete model:

$$k^{2} \cdot (R_{B} - R_{A}) - 2 \cdot k \cdot R_{B} \cdot l_{0} + R_{B} \cdot l_{0}^{2} = 0, (20)$$

where

$$k = \frac{2 \cdot R_{B} \cdot l_{0} - \sqrt{\left(-2 \cdot R_{B} \cdot l_{0}\right)^{2} - 4 \cdot \left(R_{B} - R_{A}\right) \cdot R_{B} \cdot l_{0}^{2}}}{2 \cdot \left(R_{B} - R_{A}\right)}.$$
 (21)

In the subsequent computations of the reaction to the action of the piston to the cylinder block in the analog model, Fig. 4 was used and the computation procedures adopted in the discrete model were retained.



Fig. 4. Piston load in the analog model

# RESULTS

The following dimensions and exploitation parameters of the pump were assumed in the calculations:

- pump pressure  $p_t = 32 \times 10^6$  Pa,
- pump suction  $p_s = 0$  Pa,
- shaft angular velocity  $\omega = 157$  rad/s,
- central spring force  $F_{spr} = 75$  N,
- total mass of the piston and slipper  $m_c = 0.07$  kg,
- coefficient of friction between the piston and cylinder  $\mu = 0,1$  [3],
- coefficient of friction between the slipper and the swash plate  $\mu_{e} = 0,004$  [9],
- coefficient of pressure loss at the slipper C = 0.9 [4],
- swash plate inclination angle  $\alpha = 16^{\circ}$ , \_
- distance between the centre of the joint to the slipper base e = 0.01 m,
- distance between the gravity centre of the slipper and piston and the piston front c = 0,028 m,
- distance between the gravity centre of the piston and slipper and the centre of the joint f = 0.02 m,
- piston diameter d = 0,015 m,
- internal radius of the slipper chamber  $r_{ws} = 0,00498$  m, external radius of the slipper chamber  $r_{zs} = 0,0101$  m,
- \_
- length of the sleeve leading the piston  $l_0^3 = 0,033$  m,
- radius of the positioning of the pistons  $r_p = 0.035$  m, angular coefficient of the cylinder port  $\alpha_c = 26,109^\circ$ ,
- angular coefficient of the valve plate bridge (overlap)  $\alpha_m = 44,674^{\circ}.$

As presented in Fig. 5, the values of reactions were obtained in the calculations as a function of the angle  $\varphi$ of the cylinder rotation in the discrete model. The values of the friction force (1) depending on the cylinder rotation angle are presented in Fig. 6.



Fig. 5. Reaction as a function of the angle  $\varphi$  of the cylinder rotation in the discrete model



**Fig. 6.** Friction force  $F_{Td}$  as a function of the angle  $\varphi$  of the cylinder block rotation in the discrete model

On the basis of the calculations it can be observed that the friction force (1) occurring in the kinematic pair piston-cylinder block in the pressure zone is about 4 to 8 % of the pressure force (3) in the discrete model.

Fig. 7 presents reactions in the analog model and Fig. 8 shows a comparison of the friction forces occurring between the piston and the cylinder obtained in the analog and discrete models.



**Fig. 7.** Reactions  $R_A$  and  $R_B$  as a function of the angle  $\varphi$  of the cylinder block rotation in the analog model



**Fig. 8.** Friction force  $F_{Tc}$  for the analog model and  $F_{Td}$  for the discrete model depending on the cylinder rotation angle

In the analog model the ratio of the friction force (1) to the pressure force (3) is about 7 to 13%.

# CONCLUSIONS

The following conclusions can be stated on the basis of the present study:

- The computation models of the piston load enable the assessment of friction forces and piston load depending on the cylinder rotation angle. The models can be employed for designing the kinematic pair pistoncylinder block in axial piston pumps.
- The significantly high values of the friction force between the piston and the cylinder press the cylinder block towards the valve plate in the pump operation

system and in the opposite direction in the motor operation system.

3. The analog model of the piston load is more reliable than the discrete model due to the fact that the gap height between the piston and cylinder is small.

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# OBCIĄŻENIE PARY KINEMTYCZNEJ TŁOCZEK-CYLINDER W POMPIE WIELOTLOCZKOWEJ OSIOWEJ

S tr e s z c z e n i e. W pracy przedstawiono analizę obciążenia pary kinematycznej tłoczek-cylinder w pompie wielotłoczkowej osiowej. Analizę przeprowadzono z wykorzystaniem przestrzennych modeli dyskretnego i ciągłego obciążenia tloka. Określono wartości reakcji i siły tarcia występujące pomiędzy tłokiem i cylindrem dla typowej pompy wielotłoczkowej osiowej. Symulację obciążenia przeprowadzono z wykorzystaniem programu Mathcad [15].

Słowa kluczowe: pompa wielotłoczkowa osiowa, obciążenie tłoka.

# Effect of thermal conditioning of silica-sodium glass on the kinetics of zeta potential changes during soluble sodium silicate gelation

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A b s t r a c t. The article describes the results of Zeta potential changes in the system "soluble sodium silicate - ester" according to the time of gelation. It was found out that the time of thermal conditioning of silica-sodium glass is important in terms of nanostructure elements stability of the soluble sodium silicate. Stability characteristics of these elements can affect the binding characteristics of silicate binder-quartz system, and thus their strength properties at ambient temperature.

Key words: soluble sodium silicate, silica-sodium glass, Zeta potential, thermal conditioning.

# INTRODUCTION

Soluble sodium silicate, or an aqueous solution of sodium silicate, is one of the oldest inorganic binders used in various industries. In the foundry it is a binder used in the production of the molding sands. The advantage of molding sands with the soluble sodium silicate is a good heat resistance of moulds and cores, which is especially important for medium and heavy cast iron alloy, and no emission of toxic gases in the preparation of the moulding sands, pouring forms and removing casting [4-10,11-17,19-23]. In addition to these environmental and technological considerations, economic considerations are also important. Molding sands with soluble sodium silicate are much cheaper than the moulding sands with the binder resin. Apart from the obvious advantages of moulding sands with the soluble sodium silicate, however, have several disadvantages such as too much residual strength, lower primary strength and tendency to formation of sinters. The sintering process can be reduced by reducing the amount of binder in the moulding sands, but this reduction is possible only if the improvement of its binding properties occurs.

Soluble sodium silicates usually form stable aqueous solutions, but from a chemical point of view, generally do not have a clear composition. They form durable composite structures, which are defined complexes of sodium silicate and silicic acid. Their composition varies and ranges from 4 moles of SiO<sub>2</sub> per 1 mol of Na<sub>2</sub>O and 1 mol of SiO<sub>2</sub> to 4 moles of Na<sub>2</sub>O. Thus, the general formula of sodium silicate can be written as  $xNa_2O \cdot ySiO_2$ , and values for x and y vary from 1 to 4 [18].

The main parameter that allows to distinguish between the different sodium silicates is the silica module, which is the molar ratio of silicon dioxide contribution to sodium oxide in the considered system. There are known also sodium silicate crystal structure. They derive from a hypothetical silicic acid of the formula  $H_4SiO_4$ .

$$NaH_2SiO_4 \rightarrow Na_2Si_2O_5$$
 bisilicate

$$Na_2H_2SiO_4 \rightarrow Na_2SiO_3$$
 metasilicate

$$Na_3HSiO_4 \rightarrow Na_6Si_2O_3$$
 pirosilicate

$$Na_A HSiO_A \rightarrow Na_A SiO_A$$
 orthosilicate

Some of them are in the form of readily soluble hydrates [3]. It may be noted that while the upper limit of module for soluble sodium silicate is 4, a sodium silicate for the defined limit value is the module 2. Understood is accepted hypothesis that sodium silicates, especially in aqueous solution, represent complex of silica sodium oxide, formed from simple silicates of module to 2 and silicic acid. The structural design of sodium silicate in aqueous solution is very complex due to the presence of hydroxyl ions and the adoption by the tetravalent silicon in the silicate ions sixth coordination number. Change in coordination number from 4 to 6 is facilitated by the presence of free silicon 3d orbitals, able to accept electron pairs. This gives the connections of silicon (in particular with oxygen), specific properties. Investigation of properties of aqueous solutions of sodium silicate, such as conductivity, refractive index, boiling point and freezing point, confirmed their colloidal nature. The presence and frequency of polisilicate ions (colloidal particles) emerges clearly from the module silicate equal 2. In the sodium silicate solutions with module 2 there are monosilica ions  $[H_3SiO_4]^{1-}$  and bisilica ions  $[H_4Si_2O_7]^{2-}$ , and in solutions with higher modules there are a mixture of polisilicate ions with higher degrees polycondensation. Especially at higher concentrations of SiO<sub>2</sub> and the modules M>2 identified the polymeric units containing from 4 to 8 or even 12 Si atoms [1-3].

In the solutions of sodium silicate, there is a progressive aggregation of silica from the molecular silicate to the colloidal and eventually solidified gels covering the entire solution. The possibility of interference with the rate of establishment of equilibrium in the aggregate, is used on an industrial scale to manufacture all kinds of binders and adhesives [1].

Examination of concentrated solutions of sodium silicate with module 2 to 4 by <sup>29</sup>Si-NMR method [3] showed, that the number of groups Q<sup>o</sup>, Q<sup>1</sup>, Q<sup>2</sup> decreases with increasing module, where Q is the number of siloxane bonds Si-O-Si, but increasing the number of groups Q<sup>3</sup> and Q<sup>4</sup>. For M >1.5 starts polymerization leading to the branched groups (Q<sup>3</sup>) of an average nuclearity 6 to 8, and with M>3.5 are formed three-dimensionally cross-linked units (Q<sup>4</sup>) with the surface units (Q<sup>3</sup>). Q<sup>4</sup> units was observed only at M>2.4. Assumed, however, that colloidal particles are formed at the module about 2 and at high concentrations [3].

## PURPOSE AND METHODS

To make sodium silicate glass with the assumed value of the module M = 3.3 was used sand class 1A with the chemical composition:  $SiO_2 = 99.63\%$ ,  $Al_2O_3 = 0.19\%$ , CaO = 0.09%, MgO = 0.035%,  $Fe_2O_3 = 0.016\%$ ,  $TiO_2 = 0.039\%$  and light soda with Na<sub>2</sub>CO<sub>3</sub> content = 99.30\%. Assumed volatility of Na<sub>2</sub>O equal 0,59%, which represents 2.48% Na<sub>2</sub>O loss in the melting process of glass. Oxide

composition of the silica-sodium was: SiO2 = 76.19%,  $Na_{*}O = 23.81\% + 0.59\%$  (for volatility) = 24.40%.

Melts of glass were performed in a gas furnace (oxidizing atmosphere), in the porcelain crucibles not glazed, with a capacity 3 dm<sup>3</sup>. For temperature measurement, thermocouples and optical pyrometers were used. Sets of sand and soda were dosed three times, every 40 minutes. After the last dosage alloys were kept in the crucibles at 1350°C for 60 minutes (sodium silicate glass from which the soluble sodium silicate SW-60 was made), 90 minutes (sodium silicate glass from which the soluble sodium silicate SW-90 was made) and 120 minutes (sodium silicate glass from which the soluble sodium silicate SW-120 was made).

For the dissolution of the silica-sodium glass autoclave type *VAIO-EWG 50 TR* was used. Autoclavisation performed at a temperature of about 160°C and the corresponding pressure approximately 6MPa. For correction of the module of the soluble sodium silicate, sodium hydroxide was used.

Changes in the electrokinetic potential as a function of gel time was determined for samples of the soluble sodium silicate (*SW-60*, *SW-90*, *SW-120*) mixed with the ester (ethylene glycol diacetate). A sample of formed gel was collected after 20, 30, 40, 60, 80 and 100 minutes from the time of connection ester and a soluble sodium silicate, subjected to dispersion in NaCl solution (previously filtered through a membrane filter with a pore diameter of 220 nm in order to remove insoluble impurities) and sonicated. *Zeta* potential was examined using the *ZetaSizer 3000* apparatus.

On the basis of measurements, determined the optimal composition of the electrolyte gel dispersion at which the recorded signal was the most favorable for scattered light and the measured values of *Zeta* potential were the same as when using larger dilution. After determining the *pH* value of the resulting solution, *Zeta* potential measurements were carried out. In order to characterize the sample, average potential distribution was calculated averaging the individual distributions (the sum of the individual channels and calculate the average). Two types of measurements were used in identifying changes in *Zeta* potential: as a function of gel time and after the gels, in order to characterize the surface properties of the resulting gel.



**Fig. 1.** Changes of the Zeta potential and the corresponding signal intensity *I* a laser light scattering on the surface elements of the structure formed after 20 minutes gelation process of the system "soluble sodium silicate (*SW-60, SW-90, SW-120*) - ethylene glycol diacetate"



**Fig. 2.** Changes of the Zeta potential and the corresponding signal intensity *I* a laser light scattering on the surface elements of the structure formed after 30 minutes gelation process of the system "soluble sodium silicate (*SW-60*, *SW-90*, *SW-120*) - ethylene glycol diacetate"



**Fig. 3.** Changes of the Zeta potential and the corresponding signal intensity *I* a laser light scattering on the surface elements of the structure formed after 40 minutes gelation process of the system "soluble sodium silicate (*SW-60, SW-90, SW-120*) - ethylene glycol diacetate"



**Fig. 4.** Changes of the Zeta potential and the corresponding signal intensity *I* a laser light scattering on the surface elements of the structure formed after 60 minutes gelation process of the system "soluble sodium silicate (*SW-60, SW-90, SW-120*) - ethylene glycol diacetate"



**Fig. 5.** Changes of the Zeta potential and the corresponding signal intensity *I* a laser light scattering on the surface elements of the structure formed after 80 minutes gelation process of the system "soluble sodium silicate (*SW-60, SW-90, SW-120*) - ethylene glycol diacetate"



**Fig. 6.** Changes of the Zeta potential and the corresponding signal intensity *I* a laser light scattering on the surface elements of the structure formed after 100 minutes gelation process of the system "soluble sodium silicate (*SW-60, SW-90, SW-120*) - ethylene glycol diacetate"

#### **RESULTS AND DISCUSION**

The results of studies described above are shown in Figures 1 to 6. They illustrate the changes on the *Zeta* potential and the corresponding signal intensity *I* laser light scattering on the surface elements of the structure formed after a certain time of the process of gelation of soluble sodium silicate *SW*-60, *SW*-90, *SW*-120) under the influence of the ester.

The pH of the dispersion obtained from the gel varied from  $pH \cong 11.0$  for the shortest time of gelation, to the  $pH \cong 10.3$  for gel time of 100 minutes. The pH values for individual samples little differed and had no significant effect on the Zeta potential value. As shown in the placed figures, the initial stage of gelation gives rise of the structural elements with a relatively high value Zeta potential  $\cong$  -100 mV. The signal intensity *I* of laser light scattering on the surface of these elements is high for a longer gel time, then disappears for particles with the potential  $\cong$  -40 mV. In the case of the gel obtained by the reaction of soluble sodium silicate SW-60 and SW-90 with the ester by the time 80 minutes, the signal intensity of laser light scattering on the surface of structural elements with a high Zeta potential is less than 10%. In the case of the gel obtained by the reaction of soluble sodium silicate SW-120 and ester, the signal intensity I of laser light scattering on the surface of structural elements with a high potential Zeta is significant after 80 minutes of the gelation process. As mentioned above, the signal intensity I of laser light scattering elements formed on the surface structure, can be a source of both the abundance of these elements, as well as their size and geometry of the surface (signal intensity I laser light scattering is proportional to the radius of the particles in the sixth power). It is also possible to notice the appearing and disappearing signal intensity of laser light scattering on the surface of particles contained in the reactants (soluble sodium silicate and ester). This effect is smallest in the case of gel obtained by the reaction of the ester and soluble sodium silicate SW-120, and the most visible in the gel obtained by the reaction of the ester and soluble sodium silicate SW-60. This may indicate the not full reaction of the gel reagent and a much slower reaction of soluble sodium silicate gel SW-60 in comparison to the soluble sodium silicate

SW-120. The change was deteribed in the value of the Zeta potential versus pH for soluble sodium silicate gels SW-60, SW-90 and SW-120. In the spectra signals were observed from particles of pollution of the reactants, and of the particles created in the process of nucleation. After analysis of the electrokinetic properties in the function of pH, Zeta potential values were selected for which the signal intensity I of laser light scattering on the surface elements of the structure was the biggest. The investigated electrokinetic properties of the systems resemble the properties of the "SiO<sub>2</sub> - electrolyte solutions" [18]. At the same time you can see some significant differences depending on the Zeta potential values of ionic strength. The increase in ionic strength of the carrier electrolyte causes the decrease in the absolute value of the Zeta potential, but does not move isoelectric point. These relationships are complex, which may indicate that the surface structure of the formed elements may have properties similar to the surface of a "hair", occurring on some systems with the organic phase. Some impact on the Zeta potential dependence on pH can also increase the ionic strength of the electrolyte, due to the presence of electrolyte in the sample gel. As a result, the ionic strength of the electrolyte with the lowest carrier concentration is in fact higher than expected. Comparing the Zeta potential values for the gel samples, we can conclude that the elements of the structure of the gel obtained by the reaction of the ester and soluble sodium silicate SW-90 showed the highest values potential at pH> 8, while elements of gel structure obtained by the reaction of the ester and soluble sodium silicate SW-60 has the smallest value Zeta potential.

#### CONCLUSIONS

 Zeta potential distribution after 20 minutes of gelation. All the tested types of soluble sodium silicate have similar distribution Zeta potential range from about -110 mV to about -90 mV, but in the case of the soluble sodium silicate SW-120 the corresponding signal intensity laser light scattering is the greatest. This may be attributable to a large number of particles, their large volume or the more developed surface compared to other types of soluble sodium silicate, particularly *SW-60*. The largest slenderness ratio of the peak intensity of laser light scattering in this range of values of the *Zeta* potential indicates the greatest homogeneity of elements in its structure. The second distinct peak intensity of laser light scattering on the elements of the structure of soluble sodium silicate *SW-120* corresponds to the value *Zeta* potential from about -50 mV to about -30 mV and is the smallest, compared to the peaks of soluble sodium silicate *SW-60* and *SW-90*. It seems that the potential *Zeta* distribution in this period of gelation indicates the greatest stability of soluble sodium silicate *SW-120*.

- 2. Zeta potential distribution after 30 minutes of gelation. For all the investigated types of soluble sodium silicate the heterogeneity is increased of the structure elements formed in this gelation period, with the Zeta potential from about -110 mV to about -90 mV. In the case of soluble sodium silicate SW-120, elements of the structure are disappearing of the potential from about -50 mV to about -30 mV, for the benefit of structural elements with a potential from about -80 mV to about -70 mV. In the soluble sodium silicate SW-60 practically disappearing are elements of the structure of the potential below -90 mV, while in soluble sodium silicate SW-90 is an insignificant number of elements of the structure with the Zeta potential below -90 mV. The distribution of the Zeta potential after 30 minutes of gelation, suggests similar stability elements of the structure in all the tested types of soluble sodium silicate.
- 3. Zeta potential distribution after 40 minutes of gelation. Distribution of the values of Zeta potential show increased stability of elements of the structure in the soluble sodium silicate SW-120 and SW-60 and a slight decrease in the stability of these elements in soluble sodium silicate SW-90, for which again there are elements of structures with Zeta potential from about -10 mV to about +10 mV.
- 4. Zeta potential distribution after 60 minutes of gelation. Clearly increased heterogeneity can be observed of elements of the structure arising from the gelation process of soluble sodium silicate SW-60, with the Zeta potential from about -120 mV to about -90 mV. For this type of soluble sodium silicate, there are also elements of the structure with the potential from about -80 mV to about -70 mV, from about -60 mV to about -50 mV and from about -10 mV to about +10 mV. This suggests an increasing instability of the elements of the structure of the soluble sodium silicate SW-60.
- 5. Zeta potential distribution after 80 minutes of gelation. In the case of soluble sodium silicate SW-120, after the high stability of elements of the structure, there are mainly structural components of the Zeta potential from about -50 mV to about -40 mV, indicating a significant decrease in the stability of formed structure. Also the stability is decreased of the system in case of soluble sodium silicate SW-90, in which there are

elements of the structure of the Zeta potential from about -50 mV to about -40 mV, in addition to elements of the structure of the Zeta potential from about -100 mV to about -80 mV. The most stable arrangement of the structure of soluble sodium silicate SW-60, with the Zeta potential from about -130 mV to about -100 mV and from about -100 mV to about -80 mV. Distribution of the potential in the studied types of soluble sodium silicate indicates the highest growth of gelation speed in the soluble sodium silicate SW-120, a smaller increase in the speed of gelation in the soluble sodium silicate SW-90 and the lowest speed of gelation in the soluble sodium silicate SW-60.

6. Zeta potential distribution after 100 minutes of gelation.

There has been a clear increase in the stability of elements of the structure in the soluble sodium silicate SW-120. In this silicate, elements of the structure disappeared with the Zeta potential lesser than about -90 mV, while there are elements of the structure of the Zeta potential from about -110 mV to about - 90 mV. In the case of soluble sodium silicate SW-60 and SW-90 there is a reduction in stability of the system owing to elements of the structure of Zeta potential from about -40 mV and from about -10 mV to about +10 mV.

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# WPŁYW KONDYCJONOWANIA TERMICZNEGO SZKLIWA KRZEMIANOWO-SODOWEGO NA KINETYKĘ ZMIAN POTENCJAŁU ZETA W PROCESIE ŻELOWANIA UWODNIONEGO KRZEMIANU SODU

A b s t r a c t. Opisano wyniki badań zmian potencjału Zeta układu "uwodniony krzemian sodu – ester" w zależności od czasu jego żelowania. Stwierdzono, że czas kondycjonowania termicznego szkliwa krzemianowo-sodowego ma istotne znaczenie w aspekcie stabilności elementów nanostruktury uwodnionego krzemianu sodu. Charakterystyka stabilności tych elementów może wpływać na charakterystykę wiązań układu spoiwo krzemianowe-kwarc, a tym samym na ich właściwości wytrzymałościowe w temperaturze otoczenia.

Słowa kluczowe: uwodniony krzemian sodu, szkliwo krzemianowo-sodowe, potencjał Zeta, kondycjonowanie termiczne.

# The effect of binder addition on the parameters of compacted poplar wood sawdust

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A b s t r a c t. The study discusses the results of tests investigating the effect of binder addition (calcium lignosulphonate, 0% to 20%) and moisture content (10% to 22%) on the parameters of compacted poplar wood sawdust. The susceptibility to compaction of the studied material, changes in material density and the mechanical strength of briquettes were analyzed. The addition of a binding agent increased compaction effort by 15.4% and briquette density – by 37% on average. Binder addition in the examined range resulted in an approximately 7-fold increase in the mechanical strength of briquettes at all analyzed moisture content levels.

Key words: compaction, briquetting, binding agents, calcium lignosulphonate, poplar wood sawdust.

## INTRODUCTION

The growing demand for solid biofuels [2, 16] supports the management of various types of by-products from the wood processing industry. Wood shavings, chips, bark, sawdust and wood powder account for  $20\div30\%$  of the initial mass of wood intended for processing. Most of those materials are characterized by problematic structure, low bulk density and low energy density, which is why they have to be processed into pellets or briquettes [5, 9, 10, 11].

Sawdust is a valuable raw material for the production of compacted biofuels. The particle size distribution of sawdust is generally suitable for pressure compaction without the need for further disintegration [1]. Sawdust from the wood of both coniferous and deciduous trees is used in the production process. Waste and by-products originating from various tree species have different lignocellulose composition. The most important consideration in the compaction process is lignin content whose average share in deciduous trees is 5% lower than in coniferous trees. Lignin is a natural binder which aggregates briquettes [18, 19, 20]. Sawdust from various tree species is often mixed in the production process to level out its lignin content. The above prevents technological problems, and it gives end products the required mechanical strength [3].

The above problem can also be solved by using organic and synthetic binders [12, 15]. Those compounds bind comminuted components (by acting like glue), thus improving the stability and quality of briquettes. As a result, the mechanical strength of briquettes is improved and the amount of energy required for the production process is reduced. Lignin binders are the most effective solution for compacting biological materials. They contain calcium and sodium lignosulphonates, processed starch and fatty acids. Lignin binders are used at various doses which generally do not exceed 3% of the material's weight. In line with the applicable regulations, the content of lignin binders in the production of solid biofuels should not exceed 2%. The discussed binders do not have a negative impact on biofuel combustion because they are burned in their entirety without producing additional ash, and they are completely neutral for the environment.

Binders improve material viscosity and lower its sensitivity to moisture, which supports the briquetting of materials with a higher moisture content without the risk of disintegration. This is an important consideration because sawdust from furniture and carpentry plants contains 10% to 20% of water on average. Sawdust from wet wood processed in sawmills is characterized by 50% moisture content, and it has to be dried to achieve a suitable moisture level for compacting [4, 8, 13, 17].

In view of the above, the objective of this study was to determine the values of pressure compaction parameters characterizing poplar wood sawdust with different moisture content levels and various quantities of a calcium lignosulphonate binder.

#### MATERIALS AND METHODS

The experimental material was poplar wood sawdust from a sawmill in the Lublin area. Sawdust was dried in accordance with the requirements of standard PN-EN 14774-1:2010, to achieve a moisture content in the range of 10% to 22% (every 3% +/-0.2%). The required moisture content was determined using an equation for mass change over time based on the following dependence:

$$m_1 = m_0 \left(\frac{100 - w_0}{100 - w_1}\right) (g) \tag{1}$$

where:  $m_0$  – initial mass of material, g;  $m_1$  – mass of material after drying, g;  $w_0$  – initial moisture content of material, %;  $w_1$  – moisture content of material after drying, %.

The binding agent (calcium lignosulphonate) was added to material samples with a various moisture content in the amount of 0.5%, 1%, 1.5% and 2%. Material without the binder served as the control.

The particle size distribution of sawdust was determined in accordance with standard PN-EN 15149-2:2011 using the SASKIA Thyr 2 laboratory sieve. The density of sawdust with a different moisture content was determined in bulk state according to standard PN-EN 15103:2010.

The material was subjected to pressure compaction in line with the method proposed by Laskowski and Skonecki [6] using the Zwick Z020/TN2S tensile test machine equipped with a pressing unit and a closed die with a cylinder (compaction chamber) diameter of 15 mm. Test parameters were as follows: mass of material sample – 2 g, cylinder (compacted material) temperature - 20°C, piston speed - 10 mm·min<sup>-1</sup>, maximum unit piston pressure – 114 MPa. Every compaction process was performed in three replications.

The results were used to develop a curve illustrating the correlation between compaction force and piston displacement. The values of maximum material density in compaction chamber  $\rho_c$  and total compactive effort  $L_c$ were determined based on the characteristic points of the compaction curve. The coefficient of material susceptibility to compaction  $k_c$  was calculated:

$$k_{c} = \frac{L_{c}'}{(\rho_{c} - \rho_{n})} ((J \cdot g^{-1})/(g \cdot cm^{-3}))$$
(2)

where:  $\rho_n$  – initial material density in compaction chamber, g·cm<sup>-3</sup>;  $L_c$  – unitary compactive effort, J·g<sup>-1</sup>.

The density of the resulting briquettes was determined after 48 hours of storage  $\rho_a$ .

The compaction degree of the analyzed material in the chamber  $S_{zm}$  and the compaction of the resulting briquette  $S_{za}$  were determined as the quotient of density  $\rho_c$  and  $\rho_a$ , and initial density in the compression chamber  $\rho_n$  ( $S_{zm} = \rho_c$ ,  $\rho_n^{-1}$ ,  $S_{za} = \rho_a$ ,  $\rho_n^{-1}$ ). The degree of briquette expansion  $S_{ra}$  was calculated as the quotient of density  $\rho_a$ and  $\rho_c$  ( $S_{ra} = \rho_a$ ,  $\rho_c^{-1}$ ) to evaluate the decrease in briquette density caused by turning expansion. The mechanical strength of a briquette  $\delta_m$  was determined in the Brazilian compression test [7, 14] using the Zwick Z020/TN2S tensile testing machine (with piston speed of 10 mm<sup>-min<sup>-1</sup></sup>). A briquette with diameter *d* and length *l* was compressed transversely to the axis until breaking point, and maximum breaking force  $F_n$  was determined. Mechanical strength  $\delta_m$  was calculated using the following formula:

$$\sigma_n = \frac{2F_n}{\pi \, dl} \,(\text{MPa}) \tag{3}$$

The correlations between the binder content, the moisture content of the examined material and compaction parameters were analyzed in the STATISTICA program at a significance level of  $\alpha_i = 0.05$ . The form of the equations was selected by reverse stepwise regression. The significance of regression coefficients was determined by Student's t-test. Model adequacy was verified using Fisher's test.

#### RESULTS

# BASIC PHYSICAL PROPERTIES OF MATERIAL

The results of the density of sawdust with different moisture content are presented in Table 1. The obtained data indicate that the bulk density of material in the analyzed range decreased by around -20% with an increase in moisture content.

**Table 1.** Correlation between the bulk density of material  $(\rho_{\ell})$  and moisture content (w)

w (%)	10	13	16	19	22
$\rho_s(g \cdot cm^{-3})$	0.142	0.137	0.132	0.122	0.114

The results of the particle size distribution of sawdust are presented in Figure 1. Particles measuring 1 to 1.6 mm had the highest percentage share of the analyzed samples, therefore, the material's granulometric composition was appropriate for pressure compaction.



Fig. 1. Particle size distribution (P<sub>i</sub>) of the studied material

Multiple regression equations describing the correlations between compaction parameters, the binder content and the moisture content of the experimental material are presented in Table 2. A regression analysis revealed that the studied correlations can be described by a quadratic equation of the second degree or a linear equation. The analyzed correlations are presented in Figures 2-6.

**Table 2.** Regression equations describing the correlations between density  $\rho_{c'} \rho_a$ , compactive effort  $L_c$  coefficient  $k_{c'}$  degree of compaction  $S_{zm'} S_{za'}$  degree of expansion  $S_{ra}$ , mechanical strength  $\delta_m$  and binder content  $Z_i$  and material moisture content w, and the values of determination coefficient  $\mathbb{R}^2$ .

Parameter	Regression equation	R <sup>2</sup>
Density of material in the chamber, $\rho_c$	$\rho_c = -0.003Z_l^2 - 0.032Z_l + 0.03w + 0.001Z_l + 1.391$	0.912
Briquette density after 48., $\rho_a$	$ \begin{array}{c} \rho_a = -0.044 Z_i^2 - 0.059 Z_i - \\ 0.002 w^2 + 0.015 Z_i w + 0.837 \end{array} $	0.943
Compactive effort, $L_c$	$L_c = 3.151Z_l - 1.508w + 63.89$	0.911
Coefficient of susceptibility to compaction, $k_c$	$k_c = 0.982 Z_i - 0.607 w + 23.65$	0.956
Degree of material compaction, $S_{zm}$	$S_{zm} = -0.138Z_{l} + 0.287w + 8.290$	0.923
Degree of briquette compaction, $S_{za}$	$S_{za} = -0.369Z_l^2 - 0.61Z_l - 0.011w^2 + 0.135Z_lw + 5.778$	0.904
Degree of briquette expansion, $S_{ra}$	$S_{ra} = -0.024Z_l^2 - 0.021Z_l + 0.01w + 0.008Z_l + 0.604$	0.945
Mechanical strength of briquette, $\delta_m$	$\delta_m = 0.341 Z_i - 0.037 w + 0.875$	0.973

# DENSITY OF MATERIAL IN THE CHAMBER AND BRIQUETTE DENSITY

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An analysis of the results shown in Figure 2 and regression equations (Table 2) indicated that an increase in binder dose resulted in an insignificant drop in the maximum density of material in the chamber. The above was observed at every moisture level, and a more profound decrease in maximum density was reported at a lower moisture content of 10% and 13%.

The variation of the analyzed parameter was determined in the range from 1.56 to 1.69 g·cm<sup>-3</sup>. The highest density was observed in material samples with 22% moisture content.

Briquette density (after turning expansion – 48 h) increased from 0.62 ( $Z_i=0\%$ ; w=22%) to 1.07 ( $Z_i=2\%$ ; w=13%) with the application of higher binder doses. The analyzed binding agent had the most significant impact on the density of briquettes made of material with a higher moisture content (19% and 22%). 1% and 2% addition of calcium lignosulphonate significantly reduced the effect of moisture content on the values of the examined parameter.

# COMPACTIVE EFFORT AND SUSCEPTIBILITY TO COMPACTION

The application of higher binder doses probably increased the coefficient of friction between material particles and between particles and the walls of the compaction chamber. The above led to an increase in compactive effort and the coefficient of susceptibility to compaction (Fig. 3).

The value of parameter  $L_c$  for the analyzed samples ranged from 30.32 to 54.12 J, and the value of



Fig. 2. Correlations between density of material in the chamber ( $\rho_c$ ), briquette density ( $\rho_a$ ) and binder content ( $Z_l$ ) at different moisture content levels (*w*).



Fig. 3. Correlations between compaction effort  $(L_c)$ , the coefficient of susceptibility to compaction  $(k_c)$  and binder content  $(Z_l)$  at different moisture content levels (w).

parameter  $k_c$  – from 10.82 to 20.02 (J·g<sup>-1</sup>)·((g·cm<sup>-3</sup>))<sup>-1</sup>. The values of the studied parameters were highest for the maximum binder dose (2%) and the lowest moisture content (10%). The above indicates that sawdust with a higher moisture content and without the addition of a binding agent is more susceptible to compaction.

DEGREE OF BRIQUETTE COMPACTION AND EXPANSION

An analysis of the degree of material compaction in the chamber revealed that binder dose had an insignificant effect on the values of the studied parameter (Fig. 4).

On average, the maximum density of material in the chamber  $\rho_c$  was 13-fold higher than initial material



Fig. 4. Correlations between the degree of material compaction  $(S_{zm'})$ , the degree of briquette compaction  $(S_{za})$  and binder content (Z) at different moisture content levels (w)



Fig. 5. Correlations between the degree of briquette expansion  $(S_{rd})$  and binder content  $(Z_{l})$  at different moisture content levels (w)



Fig. 6. Correlations between the mechanical strength of briquettes  $(\delta_w)$  and binder content  $(Z_i)$  at different moisture content levels (w)

density  $\rho_n$ . The highest maximum density was reported in material samples with 22% moisture content.

The results of briquette compaction analysis (Fig. 4) indicated that the density of a stored product was around 5-fold higher than the initial density in samples with 22% moisture content and no binder to around 8-fold higher one in samples with 2% binder content and the same moisture content. Binder addition increased the density of products made of materials with a higher moisture

content. The highest compaction values were noted in briquettes made of material with 19% and 22% moisture content with 1%-2% addition of binder.

The results of briquette expansion tests confirm the above observations (Fig. 5). In briquettes made of material with 19% and 22% moisture content, the addition of higher binder doses increased the analyzed parameter two-fold (from around 0.37 to around 0.6).

#### BRIQUETTE STRENGTH

The results of strength tests indicate that the mechanical strength of briquettes increased with the addition of a binding agent to poplar sawdust (Fig. 6).

Mechanical strength values were determined in the range of 0.07 to 1.29 MPa. The highest strength values were reported in briquettes made of sawdust with 13% moisture content, and the lowest – in products with 22% moisture content, at every binder dose. It should be noted, however, that 1.5% addition of the binder to material with 22% moisture content produces briquettes whose strength is identical to that of products made of pure sawdust with 13% moisture content.

#### CONCLUSIONS

The following conclusions can be formulated based on the results of this study:

- 1. The addition of a binding agent in the analyzed dose range decreased the maximum density of material in the compaction chamber by an average of -4.1%, and increased briquette density by an average of 37%.
- Sawdust's susceptibility to compaction decreased with a rise in binder dose. Compaction effort (with a binder content of 0%-2%) increased by 15.4%, and coefficient k increased by 12.5%, on average.
- 3. The degree of briquette compaction and expansion increased with a rise in binder dose at every binder content level. The highest increase was reported in the material with 19-22% moisture content where parameter  $S_{za}$  increased by 56.6% and parameter  $S_{ra}$  by 61.1%, on average.
- 4. An increase in binder content led to an approximate 7-fold rise in the mechanical strength of briquettes, regardless of the moisture content of the investigated material.

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# WPŁYW DODATKU LEPISZCZA NA EFEKTYWNOŚĆ ZAGĘSZ-CZANIA TROCIN TOPOLOWYCH

S treszczenie. Przedstawiono wyniki badań nad określeniem wpływu dodatku lepiszcza w postaci lignosulfonianu wapnia (od 0 do 2%) i wilgotności (od 10 do 22%) na parametry procesu zagęszczania trocin topolowych. W szczególności wyznaczono podatność surowca na zagęszczanie, zmiany gęstości materiału oraz wytrzymałość mechaniczną aglomeratów.

Stwierdzono, że wraz ze wzrostem dodatku lepiszcza, rośnie wartość pracy zagęszczania przeciętnie o 15,4%. Natomiast gęstość aglomeratu wzrasta średnio o 37%. Wykazano, iż dodatek lepiszcza w rozpatrywanym przedziale powoduje około 7-krotny wzrost wytrzymałości mechanicznej aglomeratów w odniesieniu do wszystkich analizowanych wilgotności surowca.

Słowa kluczowe: zagęszczanie, brykietowanie, lepiszcza, lignosulfonian wapnia, trociny topolowe.

# The usefulness of briquettes and pellets from selected plant materials for energy purposes

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S u m m a r y. This article presents the results of research on the calorific value and heat combustion of briquettes and pellets made from various plant materials. The calorific value of briquettes and pellets from wheat straw amounted to 14,958 MJ·kg<sup>-1</sup> and 15,960 MJ·kg<sup>-1</sup>, respectively, and from rye straw 15,865 MJ·kg<sup>-1</sup> and 16,627 MJ·kg<sup>-1</sup>, respectively. A slightly smaller calorific value was reported for briquettes and pellets made from maize straw: 14,134 MJ·kg<sup>-1</sup> and 15,868 MJ·kg<sup>-1</sup>, respectively. The highest calorific value (19,284 MJ·kg<sup>-1</sup>) was reported for pellets made from olive cake. Statistical analysis showed significant differences between results obtained for the combustion heat of briquettes made from wheat straw, rye straw and maize straw. Significant differences were also observed between the combustion heat of pellets made from olive cake and pellets made from the three tested varieties of straw.

Key words: energetics, straw, briquettes, pellets

# INTRODUCTION

Plant production can be a significant source of renewable materials for industry. Increasing its share in the production of energy benefits all citizens, because it helps to save fossil fuels and reduce the emission of carbon dioxide into atmosphere, which is, among other things, responsible for intense climate changes. The main by-product of plant production on farms is the straw of cereals and other cultivated plants. One of the ways of managing the surplus of straw is its utilization in energetics [Skonecki et al. 2011].

The moisture of biomass derived from agriculture assumes a wide range of values. It depends on the variety, maturity and part of the plant, and on the weather conditions. Wheat straw and rye straw have lower moisture than maize straw. In addition, the moisture of maize straw varies significantly depending on the part of the plant [Szymanek, Kachel-Jakubowska 2010].

In comparison with other commonly used energy carriers, stray in its unprocessed form is a rather burdensome energy material. This is because it is a heterogenic material, of lower energetic value, particularly when related to a unit of volume, in comparison with conventional energy carriers. In order to standardize the straw and improve its usefulness for energy purposes it is necessary to increase its volume weight, which can be done through densification of the loose straw. The densification is achieved through kneading (straw pressing). To facilitate the manipulation of straw even further, small elements (briquettes, pellets) are produced: durable rolls, bales, or other forms [Adamczyk et al. 2006, Fiszer 2009, Gradziuk 2006, Gradziuk and Kościk 2007].

In Poland, where ca 95% of electric energy is produced from coal, biomass assumes particular importance, which is reflected in the currently binding legislation. In order to facilitate the energetic utilization of biomass (transport, storage and combustion), it is processed into so-called solid biofuels, among which briquettes and pellets are of greatest importance [Bakhareva 2008]. Pellets are made by compressing the material at high pressure, without using any gluing chemical substances. They have a round cross-section with a 6-30 mm diameter and 10-50 mm length. Straw of all cereals as well as meadow grasses can be used to produce them. The growth in the use of pellets for energy purposes offers a great chance to increase the production of biomass used for making them. The obtained pellets are a fuel which can be useful both for individual heating systems and collective heating systems. They are thus particularly useful in small installations, such as boiler-houses or fireplaces in detached houses [Niedziółka et al. 2011, Hejft 2011]. Of great help are new technical solutions which make it possible to transform biomass into various forms of energy more and more efficiently and facilitate its common use.

The necessity of obtaining more and more biomass by energy plants gives farmers an opportunity to gain an additional source of income. All they need to do is collect the straw on the fields using any kind of baler and then sell it to a company which organizes the production of biomass to satisfy the needs of energetic.

#### MATERIAL AND METHODS

The aim of the research was to determine the combustion heat and calculate the calorific value of briquettes and pellets made from various materials derived from agriculture. The obtained results are supposed to show the usefulness of briquettes and pellets from various plant materials in the co-combustion with coal in professional electric power stations in Poland.

The material for research was obtained from BIOEN-ERGIA INVEST S.A., a stock company in Dobre Miasto. The research was conducted on cylindrical briquettes with ca 70 mm diameter and 10-100 mm length, and pellets with 25 mm diameter and random length. They were characterised by the so-called "fruit drop" structure (a row of interconnected, easily separable tablets of 10-15 mm length). We examined briquettes and pellets made from what straw, rye straw and maize straw, and pellets made from olive cake. After averaging samples, their moisture was determined using gravimetric method. The calorific value and combustion heat of briquettes and pellets were determined in accordance with the Polish norm PN-ISO 1928: 2002. The measurements were repeated three times for each test. The differences in calorific values did not exceed the difference specified in the procedure between two markings and amounting to 200 kJ·kg<sup>-1</sup>.

The results were analyzed statistically. Variance analysis and significance tests were conducted at the level of  $\alpha = 0.05$ , separately for briquettes and pellets, using STATISTICA 6.0 program.

# **RESULTS AND DISCUSSION**

The results of research on the calorific value and combustion heat of briquettes and pellets made from wheat straw, maize straw and rye straw, and of pellets made from olive cake, are presented in table 1 and in figure 1.

It should be stressed that the calorific value of briquettes and pellets from agricultural biomass is extremely significant for professional energetics because this index influences the price of the product delivered to the electric power station. The nominal calorific value of the material established by Polish electric power stations amounts to

Table 1. Calorific value and combustion heat of briquettes and pellets made from various plant materials

Material tested		Mass of sample before drying [g]	Mass of water [g]	Dry mass [g]	Relative moisture [%]	Enthalpy of combustion [MJ·kg <sup>-1</sup> ]	Calorific value [MJ·kg <sup>-1</sup> ]	Combustion heat [MJ·kg <sup>-1</sup> ]	
from wheat straw		10	0,742	9,258	7,42	16,458 14,958		15,237ª	
Briquettes	from rye straw	10	0,697	9,303	6,97	17,354	15,865	16,144°	
	from maize straw	10	0,752	9,248	7,52	15,636	14,134	14,460 <sup>b</sup>	
	from wheat straw	10	0,722	9,278	7,22	17,455	15,960	16,195ª	
Pellets	from rye straw	10	0,794	9,206	7,94	18,14	16,627	16,699ª	
	from maize straw	from maize straw 10		9,277	7,23	17,363	15,868	16,108ª	
	From olive cake	10	0,859	9,141	8,59	20,813	19,284	19,025 <sup>b</sup>	

Different letters in the index indicate major differences between the features tested (separately for pellets and briquettes) at the significance level  $\alpha = 0.05$ 



Fig. 1. Combustion heat of tested briquettes and pellets at specified moisture values

14,3 GJ·t<sup>1</sup>. If the producer of biomass who is contractbound with an electric power station delivers material of lower calorific value than the established one, s/he will obtain a lower price, and vice versa.

The calorific value of briquettes and pellets made from wheat straw amounted to 14,958 MJ·kg<sup>-1</sup> and 15,960 MJ·kg<sup>-1</sup>, respectively, while the value for rye straw amounted to 15,865 MJ·kg<sup>-1</sup> and 16,627 MJ·kg<sup>-1</sup>, respectively. A slightly smaller calorific value was determined for the briquettes and pellets made from maize straw; it amounted to 14,134 MJ·kg<sup>-1</sup> and 15,868 MJ·kg<sup>-1</sup>, respectively. The highest calorific value (19,284 MJ·kg<sup>-1</sup>) was determined for pellets made from olive cake.

Statistical analysis has shown considerable differences between the results concerning combustion heat of briquettes made from wheat straw, rye straw and maize straw. Significant differences were observed between the combustion heat of pellets made from olive cake and the combustion heat of the pellets made from the three tested varieties of straw.

# CONCLUSIONS

- 1. The combustion heat of pellets and briquettes depends on the plant material they are made from.
- 2. Significant differences were observed concerning the combustion heat of briquettes from wheat straw, rye straw and maize straw.
- 3. Significant differences were observed between the combustion heat of pellets made from olive cake and pellets made from wheat straw, rye straw and maize straw, while no significant differences in combustion heat were observed among the pellets made from the three tested varieties of straw.
- 4. The highest value of combustion heat, amounting to 19,025 MJ·kg<sup>-1</sup>, was observed for pellets made from olive cake.
- 5. Briquettes and pellets made from wheat straw, rye straw and maize straw, and from olive cake meet all the requirements concerning calorific value as specified by professional electric power stations.

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PRZYDATNOŚĆ BRYKIETU I PELETU Z WYBRANYCH MATERIAŁÓW ROŚLINNYCH NA CELE ENERGETYCZNE

Streszczenie. W pracy przedstawiono wyniki badań wartości opałowej i ciepła spalania brykietów i peletów wykonanych z różnych materiałów roślinnych. Wartość opałowa brykietów i peletów ze słomy pszennej wynosiła odpowiednio: 14,958 MJ·kg<sup>-1</sup> i 15,960 MJ·kg<sup>-1</sup>, natomiast ze słomy żytniej odpowiednio: 15,865 MJ·kg<sup>-1</sup> i 16,627 MJ·kg<sup>-1</sup>. Nieco mniejszą wartość opałową stwierdzono dla brykietów i peletów wykonanych ze słomy kukurydzianej, która wynosiła odpowiednio: 14,134 MJ·kg<sup>-1</sup> i 15,868 MJ·kg<sup>-1</sup>. Najwyższą wartość opałową (19,284 MJ·kg<sup>-1</sup>) stwierdzono dla peletów z wytłoków oliwki. Analiza statystyczna wykazała istotne różnice między wynikami dotyczącymi ciepła spalania brykietów ze słomy pszennej, żytniej i kukurydzianej. Istotne różnice wystąpiły również między ciepłem spalania peletów z wytłoków z oliwki oraz peletów wykonanych z trzech badanych rodzajów słomy.

Słowa kluczowe: energetyka, słoma, brykiety, pelety.

# Analysis of the influence of variable insulating power of a storing tank on energy effects in the conversion system of solar radiation

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S u m m a r y. The work presents the results of energy analysis for a system consisting of solar collectors, a heat pump, and a storing tank. Based on the formulated accounting equations, changes in the amount of the collected heat and water temperature in an accumulation tank in particular months and in a daily cycle were estimated. The amount of water in an accumulation tank and insulation power of its walls was accepted as decisive variables. Periods, when application of the system elements accepted for the analysis is rational, were determined along with dependence allowing (based on parameters of the surrounding climate and insulation power of tank walls) determination of the recommended temperature of water stored in a tank. The influence of insulation of storing tank walls on final energy effects was analysed as well.

Key words: storing tank, insulation power, solar collectors

# INTRODUCTION

The system of using heat as a result of solar radiation conversion, except for solar collectors and elements, is composed of an accumulation tank as well. In this tank, effective energy, which was formed as a result of conversion, is collected and stored enabling its most effective use by an installation user. A composition of elements, which make the system efficient both currently (during radiation) and in the periods when there is no radiation is an essential issue. Collectors and a storing tank are elements which directly decide on efficiency and exploitation characteristics of an installation. Many scientific works have been published within these issues and construction and exploitation directives, put in practice, have become a standard equipment of solar installations. However, existing technical solutions do not shut the way against new concepts, concepts analysed by many researchers from different scientific centres. Thus, Kumar and Rosen [2011] examined the collector - tank system in which a storing tank divided into two independents of variable

volume, parts was applied: one of them subjected to direct radiation, collected a heated factor and was used to satisfy current energy demands, whereas the other (thermally insulated) served for long-term heat storing. The discussed issues were determined by accounting equations and optimal participation of these volumes was determined as well. The influence of the setting angle of a collector on efficiency of storing heat was calculated. Kalogirou [1997] analysed the system consisting in a cylindrical collector and a storing tank. The considered elements of the system were described by variables used in the analysis of heat issues, a numeric programme was worked out, work efficiency was determined and economic analysis of the suggested solution was carried out. In the conclusion, it was stated that this system, compared to standard solutions (with flat collectors) brings positive energy effects whereas a period of return of the incurred financial outlays is accepted in practice. Smyth et al. [2001] presented mathematical dependencies, which are used to describe energy effects and efficiency (energetic and optical) for the system composed of a modified, as far as structure is considered, collector (of two different lengths) which has been integrated with a tank storing a heated factor. In a tank, from its top part, liquid was used to satisfy current demands, the remaining amount was stored. The authors also determined differences in efficiency in different time of diverse climatic conditions (temperature, sun exposure). In another work, the authors [Smyth et al.] carried out energy estimation, calculating the amount of heat, which was formed out of radiation conversion, received by the analysed components of the installation and the final energy efficiency. Hazami et al. [2005] analysed energy efficiency at using a modified structure of a solar collector cooperating with a standard accumulation tank. The modification of a collector consisted in using capillary pipes covered with a high solar radiation absorbent material integrated in one structure. Heated

water was directed for heating a greenhouse. Comakli et al. [2012] worked out a mathematical model (solved with the use of MATLAB application) for optimisation of collectors' sizes and for accumulation of tank volume. For variable climatic conditions, radiation conversion effectiveness was estimated and optimal tank volume was determined. Alkilani et al. [2011] carried out an overview of research works, covering analysis of materials which are subjected to a phase change (Phase Change Material) used in heat storing systems including also solar energy installations. In the discussed systems, it was commented that a proper selection of a storing medium, a degree of filling, the size of a material (a proper surface and the value of phase change heat decide on storing efficiency. They also reported necessity to carry out simulation research of operation of such installation. Szargut and Stanek [2007] worked out a two-criteria optimising model for analysis of ecology and energy issues in a flat liquid collector. Geometric parameters of a collector (a gauge and a diameter of pipes where a circulation factor flows) and a collector surface in an annual heat demand aspect constituted accepted decisive variables. Hinti et al. [2010] analysed energy effects at using a PCM body (paraffin) as a storing material. Material was placed on two layers inside a storing tank. As a result of the research they determined thermal effects of a storing factor and daily changes of its temperature in the ratio to a tank filled with water. Haillot et al. [2012] presented a mathematical model (solved mathematically) for the system consisting of a solar collector cooperating with a sequential model of an accumulation tank filled with PCM material. Each section was described with a separate equation whereas connection between particular sections occurred through connection between streams of liquid flowing in and flowing out to particular bed segments. A formulated model was subjected to a verification procedure, whereas working out the effects of storing ability for the discussed system was a final effect. Hossain et al. [2011] in his review work presented structures and mathematical dependencies for estimating energy effects of solar energy installations. Moreover, results of analysis of influence of collectors' types, structure of storing tanks (except for accumulators filled with a PCM body) on efficiency of solar radiation conversion were presented. Palacios et al. [2012] presented results for a tank inside of which thermal stratification of water collected was applied. At the first

stage, laboratory research were carried out (at a forced spraying of liquid into a tank by the use of nozzles), whereas at the second stage, a worked out methodology was repeated in real conditions of solar installation. As a result of the research, thermal effects of a storing factor in an accumulation tank were determined. Lima et al. [2006] presented optimisation results (with the use of the TRNSYS application) of a thermo-siphon solar installation, where they determined an optimal slope angle of a collector for diverse climatic conditions. They also determined energy outlays and incurred investment costs for functioning of a system including flat solar collectors. Kurpaska et al. [2004] analysed efficiency of energy conversion in flat solar collectors cooperating with accumulation tanks. Based on the analysis, which was carried out, efficiency of radiation conversion and efficiency of storing liquid in a tank were determined. Whereas, in the work [Kurpaska et al. 2012] results of energy efficiency analysis of flat and vacuum solar collectors operation were presented for the system, in which heated water was stored in an accumulation tank of a variable volume.

It results explicitly from a review of the research works that the issue of functioning of the solar installations energy elements is a current research problem. Therefore, the main purpose of this study is to carry out analysis of the influence of insulation changes of the heated water accumulation tank walls on energy effects of the solar radiation conversion system in a solar installation.

# MATERIAL AND METHODS

A system consisting of solar collectors and an accumulation tank is the object of the research. This system can be found in facilities of the Department of Production and Power Energy of the University of Agriculture in Kraków. Heat reception from a tank is carried out through a membrane exchanger, which is connected to a compressor heat pump. Warm water heated in result of solar radiation conversion constitutes a lower source of a heat pump at the same time. Heat is supplied to the laboratory plastic tunnel from a buffer tank of a heat pump through a heating system (a standard system and exchangers of a liquid-air type). Fig. 1 presents a scheme of a research stand.



Fig. 1. A schematic representation of a laboratory stand for analysis of solar radiation conversion in the hybrid system

An issue on cooperation of the said system with an accumulation tank of variable insulation power constitutes a discussed problem. Fig. 2 presents a scheme of the said system along with accepted symbols. Analysis was carried out based on Pluta's methodology [2000].



Fig. 2. Components of tank balance

The following constitute elements of thermal balance of an accumulation tank:

- energy stream (of useful heat) q<sub>u</sub> supplied to a tank from a solar collector,
- energy stream received from a tank by a user (tank load) q\_,
- heat losses from a tank to environment- q<sub>str</sub>.

Full tank mixing of average water temperature  $T_s$  was assumed in the analysis (water storing occurs without thermal stratification). According to the accepted symbols, equation, which influences change of water temperature, takes the following form:

$$V_s \rho_w c_w \frac{dT_s}{d\tau} = q_u - q_s - q_{str} \tag{1}$$

Heat losses bound from the heat of water pipes, which transport water from a tank to a system user, were omitted in the analysis.

Particular components of heat balance were calculated out of the following dependencies:

$$q_u = A_k F_R \Big[ G_\beta(\tau \alpha) - U_k \big( T_S - T_{ot} \big) \Big]$$
(2a)

$$q_s = m_s c_w \left( T_s - T_{s1} \right) \tag{2b}$$

$$q_{str} = U_s A_s \left( T_s - T_{ot} \right) \tag{2c}$$

As a result, upon including equations (2a, 2b and 2c) a standard line differential equation in relation to a temporary water temperature change in a tank  $(T_s)$  is obtained in the following form:

$$V_{s}\rho_{w}c_{w}\frac{dT_{s}}{d\tau} = A_{k}F_{R}\left[G_{\beta}(\tau\alpha) - U_{k}\left(T_{s} - T_{ot}\right)\right] - -m_{s}c_{w}\left(T_{s} - T_{s1}\right) - U_{s}A_{s}\left(T_{s} - T_{ot}\right)$$
(3)

This equation was solved with finite differences method with a constant time step $\Delta \tau$ . Considering a weak

variability during functions which appear in this equation and high thermal volume of water in a tank, application of the explicit differential schemes ensures a stable solution even for one-hour time steps [Pluta, 2000]. Therefore, in a differential notation (3) this equation is reformulated as follows:

$$T_{s}^{\tau+\Delta\tau} = T_{s}^{\tau} + \frac{\Delta\tau}{V_{s}\rho_{w}c_{w}} \Big\{ A_{k}F_{R} \Big[ G_{\beta}(\tau\alpha) - U_{k} \big(T_{s} - T_{ot}\big) \Big] - m_{s}c_{w} \big(T_{s} - T_{s1}\big) - U_{s}A_{s} \big(T_{s} - T_{ot}\big) \Big\}$$
(4)

Particular symbols stand for: V<sub>s</sub>- water volume in an accumulation tank, m<sup>3</sup>;  $\rho_w$ - water density, kg·m<sup>-3</sup>;  $c_w$ - water specific heat; kJ·kg<sup>-1</sup>·K<sup>-1</sup>; A<sub>k</sub>- collectors surface area, m<sup>2</sup>; F<sub>R</sub>- coefficient of heat removal from collectors, [-]; G<sub>β</sub>- energy of total radiation which gets to a collector, kJ·m<sup>-2</sup>·hour<sup>-1</sup>; τα- transmission and absorbency coefficient for radiation which gets to a collector, [-]; U<sub>k</sub>- substitution coefficient of heat losses from the surface of a collector, W·m<sup>-2</sup>·K<sup>-1</sup>; T<sub>ot</sub>- environmental temperature, °C; m<sub>s</sub>- water stream collected by a user, kg·hour<sup>-1</sup>; T<sub>s</sub>, T<sub>s1</sub>- temperature of supply and return of water, which supplies a heat receiver, °C; U<sub>s</sub>- coefficient of heat transfer through the surface of an accumulation tank, W·m<sup>-2</sup>·K<sup>-1</sup>; A<sub>s</sub>- heat exchange surface of an accumulation tank, m<sup>2</sup>.

From the presented form of this equation, it results that, in the first stage, water temperature in a tank should be accepted, and then new temperature in time should be calculated  $\tau+\Delta\tau$ , which is a temperature in the next time step.

Therefore, while having a value of solar radiation intensity in the next hours of solar operation, value  $G_{\beta}$ should be added. Thus, the following methodology was applied: firstly, solar declination was calculated from Cooper's formula, then hour angle of solar radiation and equivalent radiation angles on the sloping surface (surface of collectors) and the horizontal surface were determined. Correction factors of direct, diffusion and reflection radiation were calculated in the next stage. The given procedure was applied for particular hours of solar operation in the months accepted for analysis.

A compressor heat pump of an average coefficient of energy efficiency COP=1.8 was assumed as a heat receiver. For this case, at an accepted temperature difference  $(T_s - T_{sl})$  water mass stream received by a receiver was calculated.

#### **RESULTS AND A DISCUSSION**

Analysis was carried out for the following data: water volume in an accumulation tank  $V_s = 2$  and  $6m^3$ ; initial water temperature in a tank  $T_{st=0}=10^{\circ}$ C; surface of heat exchange of an accumulation tank  $A_s=22m^2$ ; coefficient of heat penetration through a tank cover,  $U_s = 2.5$ ; 2; 1.5; 1; 0.5 and 0.3 W·m<sup>-2</sup>·K<sup>-1</sup>; collectors surface  $A_k=12,1m^2$ ; coefficient of heat losses from collectors  $U_k=6$  W·m<sup>-</sup> <sup>2</sup>·K<sup>-1</sup>; coefficient  $F_R=0.7975$ ; stream of water collected by a receiver,  $m_s = 310$  kg·hour<sup>-1</sup>; temperature difference  $T_s - T_{sl} = 5K$ . Angle of inclination of collectors (constant for the discussed period) equal to 43° was assumed in the analysis and a constant value albedo on the level of 0.2 was accepted. Calculations were carried out for a town located at the latitude 52°N (Warsaw) for which radiation data (diffusive and direct) and temperature values of air were available.

Fig. 3 and 4 presents change of water temperature in a tank as a function of variable heat losses coefficient in a tank for two exemplary months (January, June).

When analysing the course of these dependencies, it may be determined that the change of insulation of a tank casing (resulting in changed amounts of heat transferred from a tank to the surrounding air) results in a varied final water temperature in a tank. At the initial water temperature in a tank (10°C) which was assumed for calculations, increase of walls insulation results in decreasing heat losses (for a period when the temperature of environment is lower than the water temperature in a tank), in case of a reverse relation, a reverse tendency occurs. Simultaneously, it may be noticed that the increased water amount collected in a tank results in less differences in the course of the collected water temperature changes.

Fig. 5 and 6 presents daily courses of heat balance changes (as a difference between heat obtained from collectors and heat losses to environment and heat used for operation of a heat pump) for the months above listed.

As it may be noticed, cooperation of a heat pump is impossible in January as is would require that heat necessary for heat pump operation be delivered to a tank. Whereas, in June this cooperation is possible, since heat from solar radiation conversion fully covers heat demands for pump operation and additionally there is a possibility to use it for other purposes (e.g. to water plants). One may notice that the change of tank insulation causes diversity in the final heat balance. Moreover, variable tank volume influences an hour course of heat balance value.

It results explicitly from the presented values that in summer, storing heat in a tank of higher insulation power is more rational due to the assumed real parameters of the operation system elements. For example, in May, depending on tank insulation power, there is



Fig. 3. Daily change of water temperature in a tank for January



Fig. 4. Daily change of water temperature in a tank for June



Fig. 5. Daily change of heat balance elements in January



Fig. 6. Daily change of heat balance elements for June

 Table 1. presents results of calculations of heat balance for the discussed cases.

Table	1.	. A month	ly course of	heat b	alance c	hanges	(MJ	) for	diversi	ified	l insul	ation an	d water vo	lume	in an accumu	lati	ion tan	ık
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specification		months											
$V_s, m^3$	$U_s, W \cdot m^{-2} \cdot K^{-1}$	Ι	II	III	IV	V	VI	VII	VIII	IX	Х	XI	XII
2	2,5	-71	-62	-20	72	183	265	306	283	167	69	-18	-40
	2,0	-66	-58	-18	73	182	263	305	281	166	68	-17	-37
	1,5	-61	-54	-16	73	181	262	303	279	165	68	-15	-34
	1,0	-56	-49	-14	73	180	260	301	277	164	68	-13	-31
	0,5	-51	-45	-11	73	179	259	299	275	163	68	-12	-28
	0,3	-48	-43	-11	73	179	258	298	275	163	69	-11	-27
	2,5	-94	-82	-45	68	199	288	333	308	179	61	-41	-54
	2,0	-87	-76	-41	68	197	286	330	305	177	61	-38	-50
6	1,5	-80	-70	-38	69	196	283	327	302	176	61	-35	-46
	1,0	-73	-64	-34	70	194	280	324	299	174	61	-32	-43
	0,5	-66	-58	-31	70	192	278	321	296	173	62	-29	-39
	0,3	-63	-55	-29	70	192	277	320	295	172	62	-27	-37

a surplus in the final heat balance daily from 179 MJ (for  $U_s = 0.3 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ , a tank of  $V_s = 2\text{m}^3$ ) to 192 MJ (for  $U_s = 0.3 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ , a tank of  $V_s = 6\text{m}^3$ ). It may be also noticed that for the discussed system, using a hybrid system only from April to October is justified. In other months, exploitation is not energy justified. For the whole year an energy surplus is in the range from 1018 ( $U_s = 0.3 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ , tank of  $V_s = 2\text{m}^3$ ) to 1041 MJ ( $U_s = 0.3 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ , tank of  $V_s = 2\text{m}^3$ ) to 1041 MJ ( $U_s = 0.3 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ , for  $V_s = 6\text{m}^3$ ). Obviously, this result would be different in case of assuming different water temperature in an accumulation tank.

Having formulated dependencies, calculations for the months when the system was used (from April to October) were carried out for determination of forecast water temperature in a tank (for  $V_s = 6m^3$ ) in relation to changing conditions of the surrounding climate and insulation of tank walls. Temperature forecast should be understood as such its value for which there is no difference between temperatures at the beginning and at the end of the analysed 24-hour storing cycle.

For the obtained results, equation which was found and which includes the relation between temperature values and independent variables (the form of a power model was selected based on the highest value of determination coefficient; this relation was determined with non-linear estimation with quasi-Newton method at the retained coefficient of convergence of 0.001) takes the following form:

$$T_{pr} = -11467, 6 \cdot \sum R_{zew}^{-1,016} + 2, 51 \cdot t_{ot}^{0,576} + 0,226 \cdot U_s^{0,45}$$

Within the use: 7775≤R  $_{zew}$ ≤16363 kJ·m²; 7.97≤t  $_{ot}$ ≤ 17.57°C; 0.3≤U  $_{s}$ ≤2.5 W·m²·K²

Comparison between the forecast temperature from the suggested model and the calculated temperature was presented in fig.7.

One may notice that this comparison is convergent, therefore the dependence, which was found, may be used for determination of the suggested water temperature in an accumulation tank. From the presented dependence, it appears, that the decrease of the heat transfer coefficient of tank walls from 0.5 to  $2.5 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$  for the minimum temperature values and the sum of radiation, causes the necessity to rise the recommended temperature of almost 2.5% (calculated as a relative difference in comparison to the temperature at the minimum insulation of a tank. Whereas at the maximum values of parameters of the surrounding climate, the increase of tank insulation results in the necessity to increase water temperature in a tank of 1.7%.

# CONCLUSIONS

- 1. For the assumed elements of the system, it is energetically rational to use the discussed system from April to October.
- 2. The recommended water temperature in an accumulation tank is described by a relation:

$$T_{pr} = -11467, 6 \cdot \sum R_{zew}^{-1,016} + 2, 51 \cdot t_{ot}^{0,576} + 0, 226 \cdot U_s^{0,45}$$

Within the use: 7775≤R<sub>zew</sub>≤16363 kJ·m<sup>-2</sup>; 7.97≤t<sub>ot</sub>≤ 17.57°C; 0.3≤U<sub>s</sub>≤2.5 W·m<sup>-2</sup>·K<sup>-1</sup>

3. The increase of insulation of accumulation tank walls causes that the assumed value of water temperature for the heat receiver decreases: within the assumed range of changes of the surrounding climate parameters, the scope of relative temperature changes (for the maximum insulation power) is within the range 1.7 to 2.5%.

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# The Determination of the Parameters of a Ploughshare-Rotor Potato Digger

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Annotation. The results of this research on the technological process of potato-digging are based on plots of land where the crop has been dug up and sorted using a ploughsharerotor potato digger. The ideal parameters for the working components of the machine have been determined.

K e y w o r d s: tubers(potatoes), technological process, sorting, ploughshare-rotor potato digger, structural technical parameters, plots, potato conveyer belt.

#### **INTRODUCTION**

The mechanization of potato harvesting is widespread in Ukraine, in both farm and village economies. Thus, this is a very up-to-date question, and it is important to provide new, simple, effective and reliable machines for this purpose.

Although there now exists the possibility, in large fields, to mechanize the process and lower the expense of labor to 0.2-0.5 man hours per 0.01 hectares, on smaller garden plots the existing mechanized methods require 12-15 man hours per 0.01 hectares, that is, 25-75 times more than in large fields.

The most promising direction for research is to develop machines that have active components that dislodge and separate the potatoes are all stages of the technological process. This problem can be solved by developing apparatuses that provide intensified technological processes, that is, a special composition of the working surface of the ploughshare, which has a special form and has a special potato-digging rotor set in above it.

Those who have previously done research on the technological process and the working parts of machines for the digging and separation of potatoes, and consequently determined the parameters of such machines, include P.M. Vasilenk. V.P. Goryachkin, L.B. Pogoriliy, P.M. Nastenko, and G.D. Petrov.

An analysis of the existing technological processes and working parts of potato-digging and separation machines has revealed a poor level of separation and mechanical damage done to the potatoes, which is caused by an imperfect clod-breaking apparatus and a faulty composition of machine parts.

By analyzing the literature concerning this problem, we determined the weaknesses in the construction of existing potato harvesting machines and also determined how we can improve the technological process of potato digging by improving the efficiency of the digger ploughshare and putting in a spade rotor above it that provides an active breaking up of the soil layer.

The results of our research and development of the components of a new potato digger and separation machine can now provide villagers with small plots of land and adequate, efficient mechanical means for performing this task.

## **RESEARCH METHODS**

For the theoretical research of optimized parameters for potato digging machines we used the methods of theoretical mechanics, higher mathematics and mathematical statistics to develop a mechanical, mathematical model of the technological process. The experimental, practical research was done in a laboratory setting, planning multivariable experiments for testing and then analyzing the results of these experiments. Theoretical calculations and the statistical processing of experimental data were conducted using processing programs on a personal computer.

#### **RESEARCH RESULTS**

In the proposed construction of a potato digger (Fig. 1) the layer of soil and potatoes that is to be dug encounters blade 4, and undergoes a matching rotating movement

along with the blade and a simultaneous lateral movement. After the blade and its "contents" have turned a certain number of degrees a mass is thrown out on the surface of the field. As the blade strikes the field, this blow being concentrated at the end portion of ploughshare 3, the process of clod-breaking is improved and the level of separation is thus improved as well. The working parts of the digging apparatus are shown in diagram 1.

We conducted theoretical research on the mutual interaction of the ploughshare and the soil layer the characteristics of the movement of the dug-up mass along its surface(both above and below).



Fig. 1. Technological potato digger plan

In Fig. 2 we show the forces which act upon the ploughshare. at point A the soil layer is cut; at point E at the curvature the lower part of the layer is deformed; at point H the layer is deformed from the top side. On the surface, from point H cuts are made that begin the process of separation.



Fig. 2. Forces that act on the ploughshare

Force of resistance *of P*, which operates on the ploughshare, is represented as a vector sum:

$$\overline{P} = \overline{P}_1 + \overline{F}_2 + \overline{F}_3, \tag{1}$$

where:  $P_1$  is the force of cutting resistance,  $F_2$  is the force of friction between the ground and the underside of the ploughshare and  $F_3$  is the sum of the forces of resistance between the soil and the upper surface of the ploughshare.

After determining its component parts, the force of resistance P which the ploughshare encounters when in operation is equal to:

$$\overline{P} = \overline{K}_p l_3 + f_1 \overline{Q}_n + f_2 \overline{Q}_B, \qquad (2)$$

Where KR is the specific cutting resistance,  $f_1$  is the length of the blade; mcode  $Q_1$ , is the coefficient of friction between the blade and the soil,  $Q_L$  is the force of pressure of the blade on the soil,  $f_2$  is the coefficient of friction at the surface of the ploughshare, and  $Q_B$  is the force of pressure between of the soil on the surface of the ploughshare.

In choosing the form of the surface of the ploughshare it is important to maximize the effectiveness of breaking up the surface without damaging the tubers themselves. For this reason, the surface of the ploughshare is designed with a variable transversal cut area, which diminishes the direction of the cutting edge, thus causing a layer to go up, being loosened from below with motion upward. This increased efficiency of the loosening process is arrived at by rounding off the form of the lateral walls of the ploughshare. The curved surface of the ploughshare reduces sticking, which is the chief complication in the process itself

In the cutting area of the ploughshare the monolith of soil is broken up at the same time when the mixture of soil and potatoes enters the machine. When soil is worked up by the ploughshare, forces are exert on the areas of contact of the transversal cut S and the cut A-An (Fig. 3).



**Fig. 3.** Characteristics of soil output when the ploughshare of the potato digger is in motion.

It is a known fact that the soil becomes disrupted and rises up when it is pressed upon. The distribution of forces at the intersection of disruption A-An is not the same for all heights.

By experiment it was determined that total frictional force F for the movement of the soil/potato mixture along the surface of the plowshare is:

$$F = \frac{f P' L \sin 2\alpha}{S_1} \tag{3}$$

where: f is the coefficient of friction of the soil on a ploughshare, P' is the force of pressure of the ploughshare in pounds, L is the perimeter of the cross-section of the ploughshare in meters;  $\alpha$  is the tilt angle of the ploughshare (out of the horizontal position) in degrees;  $S_1$  is the area of the cross-section of soil through the line a-a in  $m^2$ .

As a result of analyzing the dependence of the speed of the mixture V as it moves along the surface of the
ploughshare on the speed at the potato-digger V, it was determined that the maximum allowable speed for the motion of the soil/potato mixture is 0,4 m/sec, with a tilt angle of  $\alpha = 12^{\circ}$  for the ploughshare. As V is increased, and the angle  $\alpha$  increases, there is a danger of soil accumulating ahead of the plough surface.

Thus, on the basis of the experiments we did, an optimal form of the surface of the ploughshare has been determined (Fig. 4), its geometric parameters being: the width of the front part of the ploughshare a=415 mm, the width of the back part of the ploughshare b=361 mm; the length of the ploughshare 1=475 mm; the height of the ploughshare h=150 mm.



Fig. 4. The plougshshare structure

In order to determine the parameters for the rotor blade, we examined the relative motion of the tubers C (Fig. 5) on the surface of the rotor blade. At a certain moment the position of the rotor blade O1 K is give as the angle  $\psi = \psi_0 + \omega t$ , where  $\psi_0$  is the initial position of the rotor at time t=0;  $\omega$  is the angular speed of rotation of the rotor in radians/second, and t is the interval of time in seconds.



Fig. 5. The motion of the tubers on the surface of the blade

The vector equation of the motion of the potatoes at the surface of the blade is as follows:

$$m\overline{a} = \overline{G} + \overline{N} + \overline{F}_{T} + \overline{F}_{i}^{\ \kappa} + \overline{F}_{i}^{\ \kappa}, \tag{4}$$

where: m in is the mass of the potatoes in kg.,  $\bar{a}$  is the acceleration of the potatoes at the blade surface in m/s<sup>2</sup>,  $\bar{G}$  is the gravitational force on the potatoes in newtons,  $\bar{N}$  is the normal reaction at the surface of the blade, in newtons,  $F_T$  is the force of friction exerted when the potatoes rub the blade in newtons,  $\bar{F}_i^s$  is the centrifugal force of inertia of the potatoes with respect to the axis of rotation  $\bar{F}_i^\kappa$  in newtons, and is the force of Koriolis inertia in newtons.

The equation for the motion of the potatoes on the blade projected unto the fixed coordinate system  $O_1XYZ$  is:

$$m\ddot{x} = -N\sin\psi - F_T\cos\psi + F_i^k\sin\psi + F_i^e\cos(\overline{F}_i^e, x)$$
  

$$m\ddot{y} = -G + N\cos\psi - F_0\sin\psi + F_i^k\cos\psi + F_i^e\cos(\overline{F}_i^e, y)$$
(5)

where:  $\psi$  is the angle of rubbing friction in degrees, and  $\cos(\overline{F}_i^e, x) \quad \cos(\overline{F}_i^e, y)$  are the cosines of the angles of motion, where:

$$\cos(\overline{F_i}^{e}, x) = \cos\psi \frac{\sqrt{\rho_c^2 - R_{\tilde{o}}^2}}{\rho_c} - \frac{1}{\rho_c} \left[\cos\psi \sqrt{\rho_c^2 - R_{\tilde{o}}^2} - \sin\psi R_{\tilde{o}}\right]; \quad (6)$$
$$\cos(\overline{F_i}^{e}, y) = \sin\psi \frac{\sqrt{\rho_c^2 - R_{\tilde{o}}^2}}{\rho_c} + \frac{1}{\rho_c} \left[\sin\psi \sqrt{\rho_c^2 - R_{\tilde{o}}^2} + \cos\psi R_{\tilde{o}}\right], \quad (7)$$

where: R6 is the radius of the tuber in meters, mcode; cc is the radius in meters of the position of the center C of the potatoes with respect to the  $O_1$  axis.

Solving (5), (6) and (7) we find that:

$$m\ddot{x} = -N\sin\psi - fN\cos\psi + 2m\omega V\sin\psi + + m\omega^{2}(\cos\psi\sqrt{\rho_{c}^{2} - R_{\delta}^{2}} - \sin\psi R_{\delta}) m\ddot{y} = -mg + N\cos\psi - fN\sin\psi - 2m\omega V\cos\psi + + m\omega^{2}(\sin\psi\sqrt{\rho_{c}^{2} - R_{\delta}^{2}}\cos\psi R_{\delta})$$
(8)

As the potatoes perform constant motion the projected acceleration of point C will be  $\ddot{X} = 0$ ,  $\ddot{Y} = 0$ . Calculating we find that:

$$-N\sin\psi - fN\cos\psi + 2m\omega V\sin\psi + + m\omega^{2}(\cos\psi\sqrt{\rho_{c}^{2} - R_{\delta}^{2}} - \sin\psi R_{\delta}) = 0 \\ -mg + N\cos\psi - fN\sin\psi - 2m\omega V\cos\psi + + m\omega^{2}(\sin\psi\sqrt{\rho_{c}^{2} - R_{\delta}^{2}}\cos\psi R_{\delta}) = 0 \end{cases}$$
(9)

Reducing system (9) we find the value of the normal reaction at the surface of the blade:

$$N = \frac{mg}{\sin\psi(tg\psi + ctg\psi)} + 2\boldsymbol{m}\omega V - \boldsymbol{m}\omega^2 R_{\delta} \quad (10)$$

The equation for the moments of rotation of the potatoes around its axis is:

$$I_{\delta}\ddot{\xi} = Mr - FTR_{\delta}, \text{ or } \frac{2}{3}mR_{\delta}^{2}\ddot{\xi} = NR_{\delta}tgV - fNR_{\delta}, \quad (11)$$

where:  $I_b$  is the moment of inertia of the potatoes with respect to their center in kg-m;  $\ddot{\xi}$  the angular acceleration of the rotational motion of the potatoes in rad/s<sup>2</sup>, and Mr is the moment of rubbing friction of the potatoes in newton-m.

From equation (11) we determine that:

$$\ddot{\xi} = \frac{2}{3}(tgV - f) \left[ \frac{g}{R_{\delta} \sin\psi(tg\psi + ctg\psi)} + \frac{2\omega V}{R_{\delta}} - \omega^2 \right].$$
(12)

Taking into account that  $\psi = \psi_0 + \omega t$ , and  $V = R_{\delta} \dot{\xi}$ , making the corresponding transformation we find that:

$$\frac{d^2\xi}{d\psi^2} - \frac{A_1}{\omega} \cdot \frac{d\xi}{d\psi} = \frac{A_2}{\omega^2} \cos\psi - \frac{A_3}{\omega^2},$$
(13)

where: 
$$3\omega(tgV - f) = A_1; \frac{3}{2}(tgV - f)\frac{g}{R_{\tilde{o}}} = A_2;$$
  
 $\frac{3}{2}(tgV - f)\omega^2 = A_3.$ 

The solution of equation (13) is performed by numerical methods, initially setting the condition for the initial entrance of the potatoes into the blade mechanism:

$$N = F_i^k - G\cos\psi + F_i^s\sin\psi' > 0.$$
<sup>(14)</sup>

Taking into account that when the potatoes are first taken in, the normal for N=0,  $\omega^2 R_6 - g \cos \psi - 2m\omega V > 0$ ,  $a \dot{\xi} = d\xi/dt$ , the dependence of the angle of entrance of the potatoes when cut off by the blade can be written as the condition:

$$\psi > ar \cos(\frac{\omega^2 R_{\tilde{o}} - 2\omega \dot{\xi} R_{\tilde{o}}}{g}). \tag{15}$$

The solution of equation (13) then takes the form:

$$\xi = \frac{\omega t}{2} + \frac{3g(tgv - f) \cdot \sin\frac{\omega t}{2}}{2\omega^2 R_{\delta}}$$

$$\frac{\left[\sin(\frac{\omega t}{2}) - 3(tgv - f) \cdot \cos(\frac{\omega t}{2})\right]}{\left[9 \cdot (tgv - f)^2 + 1\right]}.$$
(16)

Differentiating equation (13) with MathCadi for  $\xi$ , we obtain the following value for the angular velocity of the tubers:

$$\dot{\xi}(t) = \frac{\omega}{2} \left( 1 + \frac{3 \cdot g \cdot (tg\theta - t)}{g\omega^2 R_{\delta} \sqrt{9 \cdot (tg\theta - f)^2 + 1}} \cdot \frac{1}{\sin \omega t + \operatorname{arctg}(3(f - tg\theta))} \right)$$
(17)

In Fig. 6 we see the dependencies of the angle of introduction on the angular velocity and the radius of the potatoes (going from the equality  $\psi_s = \arccos(\omega^2 R_o - 2\omega \dot{\zeta} R_o)/g)$ .



**Fig. 6.** The dependencies of the angle of introduction on angular velocity  $\psi_{e}$ , for the angular velocites  $\omega$ : 1, 2, 3, 4 corresponding to R<sub>b</sub>= 0,06; 0,04; 0,25; 0,01 m

It was determined that with a radius for the potatoes  $R_b^{=} 0.06$  m, and an angular velocity of rotation of the blade  $\omega=9$ , ..., 11 rad/s, the potatoes are thrown out at an angle of  $\psi_e=70,...,75^0$ .

#### CONCLUSIONS

- Existing technologies for digging potatoes, using traditional means do not properly break up the potato bearing soil to its full extent, especially when the soil is moist (soil sticks to the moving parts, thus greatly reducing the efficiency of the separation process. The way to improve the efficiency of this process is use a ploughshare- rotor blade system.
- 2. Examining the motion of the soil/potatoes mixture on the surface of the ploughshare we determine its optimal form and parameters. The optimal angle for the set of the plough is  $\alpha$ =12° with at machine speed of V<sub>H</sub>=0,4 m/s. Increasing the machine speed and the ploughshare angle,  $\alpha$ , lead to a dangerous accumulation of soil in front of the surface of the plough.
- 3. By mathematically modelling the motion of the potato producing soil, we have obtained the theoretical dependency of its motion as it is lifted up on the surface of the ploughshare.
- 4. We made a mathematical model that characterizes the relative, reciprocal motion of the processed mixture on the surface of the rotor blade. As a result of the analysis, we determined that the necessary distance for the thrown potatoes is between 0,8 and 1,1 m. and that the optimal values are obtained for an angular velocity for the blade of  $V_0=3$  m/s and a blade length  $l_1=0,44$  m.

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