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# A New Method of Polyethylene Pipe Extrusion Using a Specially Constructed Extrusion Head

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**Summary.** A new method of polyethylene pipe extrusion using a specially constructed extrusion head was presented in this article. A significant feature of the head is that parts of the conical core of the conical nozzle and the nozzle part of the core are on their surfaces spaced by coils in helical path, which are shifted relatively to each other. They form a channel in which the flowing plastic is twisted in a helix. Pipes shaped in this way have a higher mechanical strength.
**Key words:** extrusion method, pipe, plastic.

## INTRODUCTION

A new design of extrusion head for manufacturing of polyethylene pipes was presented in this article. This head allows for the extruding of pipes with increased mechanical strength using standard extrusion processing line. Head design is relatively simple and its implementation and use in technology does not cause problems.

Prerequisites for solving this problem have been plastic processing properties, namely, an increase in strength as a result of elongation of the polymer chain and its rotation [16]. During operation, a pipe for use in gas transmission or waterworks undergoes some stress as a result of internal pressure.

Figure 1 shows the plane state of stress in the pipes during axial tension with longitudinal force $Q$ and the internal pressure $p$.

In this state of the load pipe, components of principal stresses are specified by dependencies [10, 11]:

$$\sigma_x = \frac{Q}{F} + \frac{pD_{sr}}{4e}, \qquad \sigma_y = \frac{pD_{sr}}{2e}, \qquad \sigma_z = -\frac{p}{2}, \quad (1)$$

where:
$\sigma x, \sigma y, \sigma z$ – respectively, stress: axial, circumferential and radial,
$D$ – pipe diameter,
$e$ – pipe wall thickness,
$F$ – cross-sectional area of the pipe.

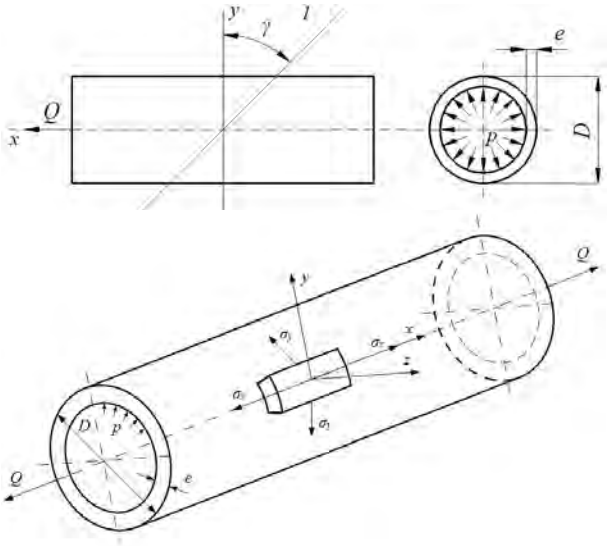


**Fig. 1.** Schema of plane stress in the pipe at an axial tensile strength of force $Q$ and internal pressure $p$

If it is assumed that the pipe is only loaded with internal pressure $p$, and the axial force is zero $Q = 0$, the axial and circumferential stresses are related to the relationship:

$$\sigma_y = k\sigma_x . \quad (2)$$

The coefficient $k$ is the aspect ratio of stress.

It is assumed that uniform deformation should occur in the pipe wall:

$$\varepsilon_x = \varepsilon_y = \varepsilon . \quad (3)$$

Dependence of the the aspect ratio of stress (coefficient $k$) and the $\gamma$ angle has the form:

$$\cos 2\gamma = \frac{1-k}{1+k}. \tag{4}$$

After the transformation the pattern is obtained, that determines the aspect ratio of the stress (coefficient $k$) at a certain angle $\gamma$.

$$k = \tan^2 \gamma. \tag{5}$$

This means that the quotient of the strain is:

$$\frac{\sigma_y}{\sigma_x} = k = \tan^2 \gamma. \tag{6}$$

The coefficient $k$ is related to the angle $\gamma$ by the relation (5). The obtained values are: $tan^2\gamma = 2$ and angle $\gamma = 54^o45'$. Thus, by changing the value of the angle $\gamma$ it is possible to change the proportions of stresses occurring in the wall of the tube. This creates a large pipe design options which meet various criteria, such as maximum strength at minimum weight.

It can therefore be argued that in the extrusion of PE pipes, giving helical movement of plasticized layers of plastic, the mechanical strength of the pipe can be increased, and particularly resistance to internal pressure in the pipe. To meet this requirement, the flow of plastic through the extrusion head nozzle channels should be subjected to circumferential stress. For this purpose, heads with rotating pin or ring are used. In the literature [17, 18] many different designs of heads are described. For design solution, the closest to that shown by the authors should be the solution described in work [9]. Figure 2 shows an example of design solution of straight extrusion head, with a rotating conical core (8) driven by an electric motor through a worm gear and the clutch torque transmission.

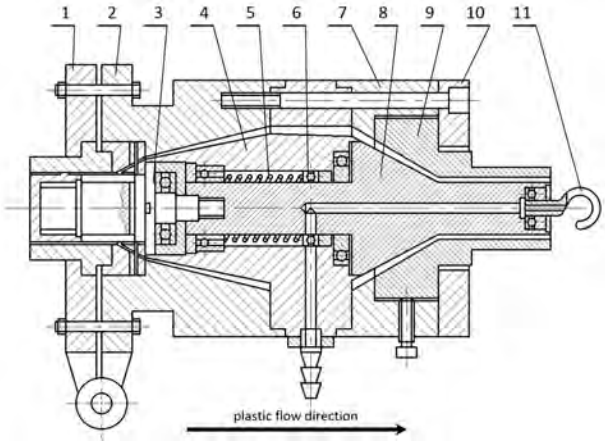


**Fig. 2.** Extrusion head for pipes manufacturing (longitudinal section): 1 – ring, 2 – housing, 3 – clutch 4 – conical core, 5 – spring, 6 – air-distribution ring, 7 – the nozzle body, 8 – conical rotating core, 9 – Part nozzle, 10 – collar, 11 – hook to attach a rope with stopper

Forming of pipe profile in the head is done by rotation of the conical core (8) relativelly to the nozzle (9). As a result of the friction, plastic moves along the axis of the head by a helicoidal motion. Axial movement of the plasticized material in the head is a result of the pressure difference in the head. It can be assumed that as a result of the axial displacement of the plastic, axial stresses $\sigma x$, are formed therein and by the rotation of the core $\sigma y$ circumferential stresses arise because the polymeric material works the tension equal to the total sum of:

$$\sigma = \sqrt{\sigma_x{}^2 + \sigma^2{}_y}. \tag{7}$$

where:
$\sigma x$ – axial stress
$\sigma y$ – circumferential stresses

Radial stresses generated by different channel diameters can be omitted.

As a result of helical movement, the specific arrangement of the polymer structure occurs, its elongation and twisting, and thus its mechanical strength is increased. Figure 3 shows the change in the mechanical strength of a pipe depending on the rotational speed $\omega r$ of the core (8) head [9].

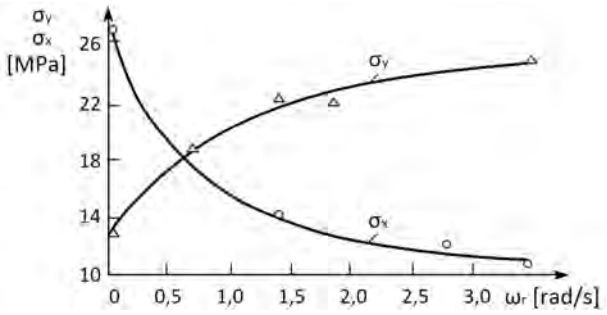


**Fig. 3.** Relation of strength $\sigma x$ i $\sigma y$ of a pipe on the rotational speed $\omega r$ of the core for high-density polyethylene: breaking stress in the circumferential and axial direction [9]

The higher $\sigma x$ component, the greater the increase in strength in the circumferential direction and the smaller one in the axial direction. From Figure 5 it can be seen that with increasing the rotational speed of the core, the strength is greatly increased in the circumferential direction ($\sigma y$) and decreased in the axial direction ($\sigma x$). The increase of rotational speed $\omega r$ of the core greatly reduces the tensile relative elongation in the direction of extrusion of plastic, and increases it in the tangential direction. This reveals a convergence of dependency between the destructive stress and relative elongation and the rotation of the core head. Presumably, this can be explained by the fact that the axis of the crystallization, which is the chain of the macromolecule is aligned along the axis of the crystallization lattice, which coincides with the direction of the total vector of movement of the plastic. This should contribute to the achievement of greater plastic strength in this direction.

The main disadvantage of the head construction solution shown in Figure 4 is a need for a propulsion in the form of a worm gear and an electric motor for rotating and controlling rotation of the core. Moreover, such a solution necessitates the use of rotating elements in the high temperatures of operation.

The extrusion head for pipe manufacturing from thermoplastic polymers, having a body which is shaped with a central core cooling hole is also known from Polish patent description of the invention [13]. In this solution, shaped core has two outer diameters, from a smooth transition between surfaces forming, and have longitudinal grooves evenly distributed on its circumference, wherein the core forming part of a larger diameter extends beyond the front of the head from a fraction to several diameters. Another solution is an extrusion head [14] consisting of a fixed part and a rotary part, equipped with a tubular element fixed at one end of the body and, at the other end, another one in the shape of a resilient protrusion sliding element embedded in the plastic flow channel.

## THE NEW EXTRUSION HEAD DESIGN

The new extrusion head design is shown in Figure 4 which shows the extrusion head in longitudinal section, while Figure 5 shows the helical coils in cross section. The extrusion head has a body (5) ended with the nozzle (7) with the shaped core attached to it (2), whose end, in the shape of a cone, is passing into a cylinder. It is located in the nozzle (7). Between the inner surface of the body, (5) the surface of the nozzle (7), and the outer surface of the core (2) there is a plasticized plastic flow channel. The conical part of the core (2) from the nozzle site (7) and the conical nozzle (7) from the core site (2) have on their surfaces coils arranged along the helical path, to allow uniform flow of the plastic. These coils are offset by half the height of the helix, and their height is ¾ of the channel height. It is necessary to adjust the nozzle body (5) in order to maintain the symmetry of the plastic tube. Plastic extruded at the final stage of the flow is directed through the nozzle (7). Its moves are helical, which is caused by the shape of helical channel.

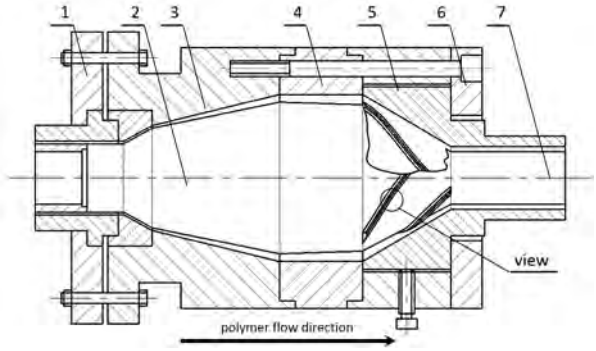


**Fig. 4.** The extrusion head (longitudinal section): 1 – ring, 2 – conical core with helical line, 3 – body, 4 – connecting ring, 5 – nozzle body, 6 – cover, 7 – part of the nozzle with helical line

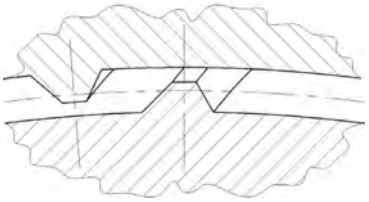

**Fig. 5.** Cross section of helical channel

The essence of the presented solution is that the conical part of the nozzle core and the conical part of the nozzle of the core are in their coils arranged on the surfaces of the helix which are offset relative to each other. In comparison with known solutions, designed construction of extrusion head allows for helical movement of extruded plastic in the final stage of the flow through the nozzle, which is forced by the stationary portion of the head.

## THE EQUATION OF THE HELICAL CHANNEL

Coils are located on the helical core head, on the outside and on the inside of the cone nozzle. The simplest, from a technological point of view, would be a helix of constant pitch. However, it does not provide an even flow of plastic. A better solution according to the authors is the distribution of the helical coils on a fixed length of the thread pitch. Coils positioned in this way provide a uniform plastic flow velocity in the channel formed by the coils. Feasibility of the helical channel on a conical surface is described in work [8].

Generally, space curve is formed by the movement of a point in the sense that it is formed by a set of subsequent positions of the point in space, namely, the point $P$ (Fig. 6) will mark a helix of constant length of each pitch of the conical surface if conditions are fulfilled. The point $P$ lies on the line $l$, which forms an angle $\alpha$ with the axis $Oz$ of Cartesian coordinate system. Straight $l$ rotates about axis $Oz$ with a constant angular velocity $\omega$. Simultaneously, point $P$ moves parallel to the axis $Oz$ with advance velocity $\upsilon(t)$. The resultant velocity $w$ of point $P$ is created by the juxtaposition of speed $\upsilon(t)$ and velocity $\omega \cdot r$ and is constant and the tangent at each point of the curve is delineated. Generally, equations of the curve of fixed length of pitch can be written on the basis of Figure 6. They take the form:

$$\begin{aligned} x &= r\cos\varphi \\ y &= r\sin\varphi \\ z &= \upsilon(t)\cdot t \end{aligned} \qquad (8)$$

where:
$x, y, z$ – coordinates of the point $P$,
$j$ – angle of line $l$,
$r$ – radius of the point $P$,
$t$ – duration of the motion of the point $P$.

The radius $r$ of a point $P$ is defined by the dependence:

$$r = r_o + z \cdot \tan\alpha , \qquad (9)$$

where:
$ro$ – smaller radius of the base of the cone,
$\alpha$ – half the opening angle of the cone.

Angle of rotation of the cone line $l$ $Oz$ axis is defined by the formula:

$$\varphi = \omega \cdot t , \qquad (10)$$

where:
$\omega$ – the angular velocity of the point $P$.

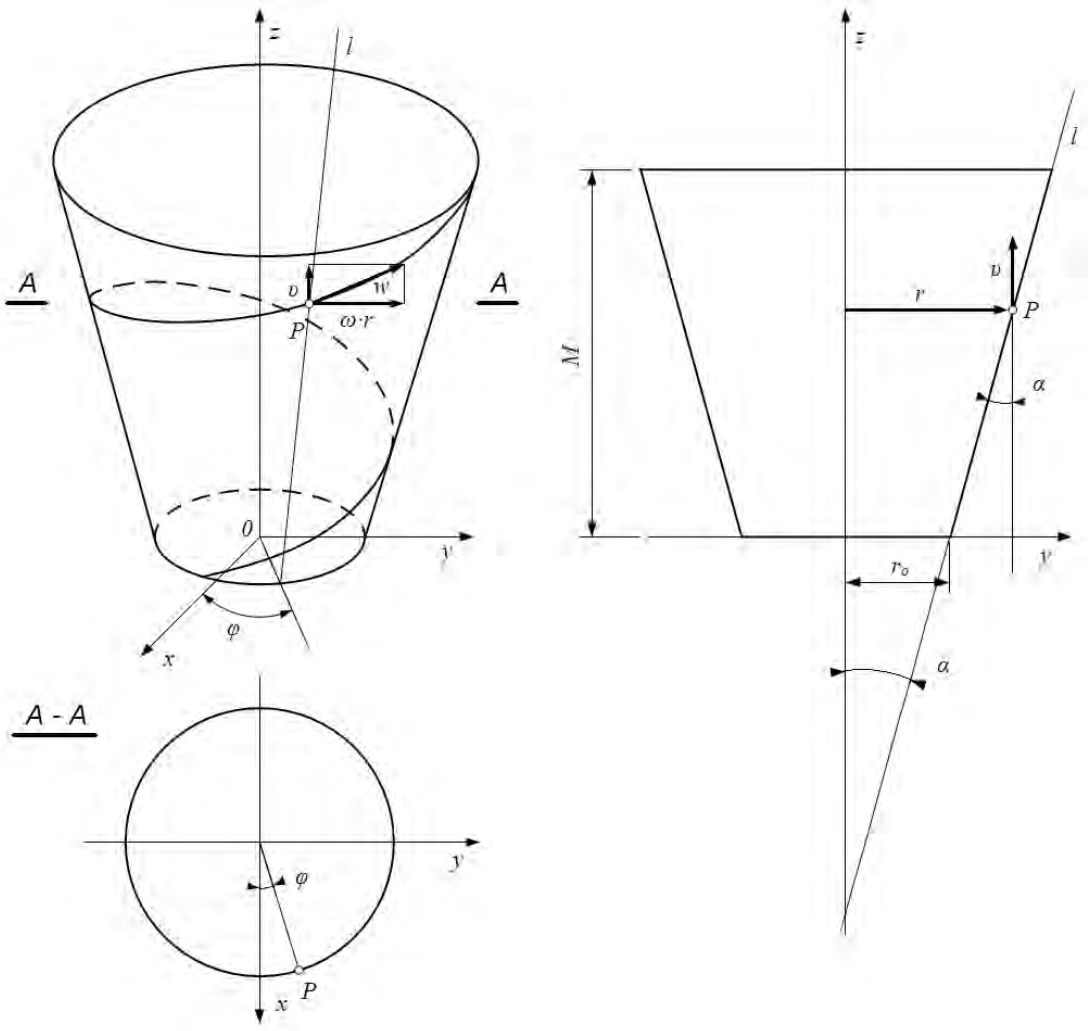


**Fig. 6.** The formation of a helically fixed length of stroke

The velocity distribution (Fig. 6) shows the following relationship:

$$\upsilon^2 = w^2 - \omega^2 \cdot r^2, \tag{11}$$

after transformation we obtain:

$$\upsilon = \omega \cdot \sqrt{\left(\frac{w}{\omega}\right)^2 - r^2}\ . \tag{12}$$

Using the relationship:

$$w = \frac{s}{t}. \tag{13}$$

where:
$s$ – the length of the helix.

Substituting equations (9), (10), (12) into equations (8) by transforming, the equation of the helix is obtained, in which the stroke length s is constant:

$$\begin{aligned} x &= \left(r_o + z\tan\alpha\right)\cos\varphi, \\ y &= \left(r_o + z\tan\alpha\right)\sin\varphi, \\ z &= \frac{\varphi\sqrt{\frac{s^2}{4\pi^2}\left(1+\varphi^2\tan^2\alpha\right) - r_o^2 - \varphi^2 r_o\tan\alpha}}{1+\varphi^2\tan^2\alpha}. \end{aligned} \tag{14}$$

## CONCLUSIONS

The presented design solution of extrusion head for polyethylene pipes is an innovative solution, that allows for the manufacturing of high-strength pipes made of polyethylene with standard extruder lines. Head design is relatively simple, and creating helical coils on the outer and inner surface of the cone can be implemented on CNC-controlled machine tools, which should not be difficult, either. This solution has been reported to the Polish Patent Office [20]. Modern meth-

ods of rapid prototyping [12] allow for easy and inexpensive prototype of nozzle head helix channel which was presented in this work. Stress states appearing in plastic pipes as well as issues related to their strength were discussed in [1-7, 15, 19]. The twisting from the present plastic flow processing through the nozzle channel with helical twist enables the production of plastic pipes which are characterized by an increased resistance to internal pressure at relatively low costs of manufacturing and retrofitting line.

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## NOWA METODA WYTŁACZANIA RUR Z POLIETYLENU Z WYKORZYSTANIEM GŁOWICY O SPECJALNEJ KONSTRUKCJI

**Streszczenie:** W pracy przedstawiono przedstawiono nowe rozwiązanie konstrukcji głowicy wytłaczarskiej do wytwarzania rur z tworzyw sztucznych, zwłaszcza z PE. Cechą charakterystyczną głowicy jest to, że część stożkowa rdzenia od strony dyszy oraz część stożkowa dyszy od strony rdzenia mają na swych powierzchniach zwoje rozmieszczone po linii śrubowej, które są przesunięte względem siebie. Tworzą one kanał, w którym tworzywo przepływające przez niego zostaje skręcone po linii śrubowej. Ukształtowana tym sposobem rura ma większą wytrzymałość mechaniczną.

**Słowa kluczowe:** metoda wytłaczania, rura, tworzywo sztuczne

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# The Use of voice Messages Generators in the Integrated Control and Supervision Systems Installed in Laboratory Rooms

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**Summary.** The correct communication between the system and user is an important symptom of correct functioning of the control and supervision system. The system status should be precisely determined by means of transferred message on the request of user or in certain situations. In case of detected hazard, the system is required to inform the user about emergency status. Such signal should make it possible to commence the hazard neutralization process or to initiate evacuation process. Often the signals informing about detected hazards are transmitted by means of acoustic signaling devices or optical – acoustic signaling devices. However, the signal does not contain any information about the type of detected hazard. The procedure to be followed in occurred situation often depends on the type of detected hazard. The laboratory room has been used in the present study as an example in order to present the cooperation of the control and supervision system based on programmable logic controllers (PLC) with the voice messages generators. The voice messages generators installed in the control and supervision system make it possible to inform the user about detected hazard and to create the voice reports informing about the status of the room being protected.

**Key words:** control systems, supervision systems, voice messages generators, PLC controllers.

## INTRODUCTION

The basic task to be performed by devices operation control systems is to ensure the correct power supply for individual devices – i.e. to perform the control and power supply function. Another task consists in the checking for the correct course of control process and in reaction to control parameters changes occurred in the actual situation – i.e. in monitoring and regulation function. The third task is to ensure the correct data exchange process in the system as well as to ensure the communication between the user and the system – i.e. management function [5,6,11,18,19]. It is possible to ensure the correct working conditions and performance of aforesaid tasks in various configurations of control system. It is also possible to apply independent autonomous control systems to control the operation of individual devices or to apply an integrated control system based upon a centralized or distributed decision making system [9, 10, 20, 21, 22].

The control and supervision systems suitable to meet the assumed needs are frequently used to manage the operation of devices installed in building structures [2, 6, 8, 9, 14]. Such systems are selected in accordance with the object's destination, user's preferences and technical capabilities of the system elements. Their task is to create the correct working conditions for installed devices, to make it possible to perform the assumed technological processes and to ensure the required safety level in the object associated with the use of the devices [11, 12, 16, 23, 24]. In the framework of the last task it is necessary to install the elements in the system in order to neutralize the occurred hazards and to warn the user about the occurred hazard. This task is performed by dedicated alarm circuits in the control and supervision systems [1, 4, 5, 12, 16]. The alarm circuits respond to manual or automatic hazard detection in the object being protected. From a technical point of view, it is defined as an assembly of cooperative devices (including wiring installation) in order to detect the hazard, to generate alarms and to initiate the undertakings intended to eliminate such hazard [1, 4].

The generally used acoustic signalling devices or optical – acoustic signalling devices belong to the basic elements making it possible to inform the user about the detected hazard. Their disadvantage consists in the generation of an identical warning signal for all the detected hazards [1, 13, 16]. The present article emphasizes the possibility to use the systems enabling the generation of voice messages adapted to current hazards and actual conditions existing in the object. The laboratory room will be used in the present study as an example in order to present the analysis for potential use of voice messages generators. The laboratory room has been

selected due to its specific working conditions, large quantity of potential hazards and various procedures to be followed in order to neutralize individual hazards. The potential use of voice messages generators will be presented on the basis of control and supervision system containing the decision making circuits based on EASY class programmable logic controllers (PLC) manufactured by Moeller. Said controllers are frequently used in the objects with defined destination and make it possible to combine the controllers together in order to increase their functional capabilities. They are capable of performing complex functions and creating complex control algorithms. The voice messages generators cooperating with the control system will perform two functions. The first one will be associated with the information transfer process to inform about the detected hazard. Another function will be associated with the creation of voice messages informing about the current object status.

## INTEGRATED CONTROL AND SUPERVISION SYSTEMS

The tasks to be performed by the modern electric installations in the buildings are not limited to the reliable supply of electricity with required parameters. Currently, there are specialized systems exercising the control over the object status and controlling the operation of devices installed therein. Therefore, the electric installations are equipped with control circuits enabling the performance of functions and procedures intended by the user. The purpose of such circuits is to accomplish the assumed goals associated with the operation of lighting, heating and ventilation functions as well as to perform the role of alarm systems informing the user about the current object status. Therefore, it is possible to improve the comfort of use, to increase the safety of work, frequently with simultaneous reduction of operation costs of such installations [5,8,9,11].

Currently there are three types of electric control system devices in the building objects:
– manual control system,
– system performing the building management functions,
– system performing an intelligent building functions.

There are two principal types of systems performing the building management functions [9]:
– island system – the system based on autonomous circuits, performing only precisely determined functions (e.g. controlling the building heating only or performing the alarm system functions only),
– integrated system – the system based on consolidated management system with concentrated or centralized structure and with open or closed architecture.

The system integration process consists in the cooperation of individual installations performing autonomous functions in the object as an integrated system performing all tasks to be performed by individual parts functioning as the components of the system. The integrated system makes it possible to control several functions and to exercise the control over several actuators in the building [8, 18, 19]

The integration of autonomous systems is possible in the following manner:
– in the form of information exchange between autonomous systems,
– in the form of detecting and actuating elements shared by the systems,
– in the form of all the control functions performed by one control system.

The problems associated with autonomous systems are eliminated in case of all the control functions performed by one control system. All elements are connected to the same controller. In case of such solution, there is only one supervising system provided with the access to all data originating from detecting elements. This system performs the assumed functions depending on operation mode (status) established by the user. The system is characterized by the lack of duplicated procedures and the fastest response to recorded events. There are much greater opportunities associated with the building of algorithm controlling the system operation but usually there is a necessity to familiarize with programming languages or to cooperate with specialized service.

## PROGRAMMABLE LOGIC CONTROLLERS USED AS DECISION MAKING CIRCUITS IN THE CONTROL AND SUPERVISION SYSTEMS

The Programmable Logic Controllers (PLC) are microprocessor based systems dedicated to devices operations and processes control. These controllers perform all functions performed by the contactor and relay control systems as well as by logics systems, programmers and discrete and continuous signals processing systems [3, 15].

PLC controllers make it possible to perform any control algorithm; obviously in the scope anticipated by the resources of said PLC controller and are associated with the number of inputs and outputs and their types as well as with the functions existing in this type of the controller (timers, clocks, counters, arithmetical and logical functions, regulators etc.). The execution of an assumed algorithm is commenced from the entry of program algorithm into its operating memory. The controller programming is possible in the local mode, directly on the controller. The built-in function buttons of the controller are used for this purpose. However, controller programming is more frequently carried out in the indirect mode. The application creation process is carried out by means of a computer on the software dedicated to the specified controller. Then the program is recorded in the controller memory. The program reading from PC computer is possible by means of communication port of the controller and appropriate conductor [3, 15].

An important feature of PLC controllers consists in their openness and versatility of use. PLC controllers are used for controlling the working processes in case of single devices as well as in the case of the whole processes and process plants [7, 9, 12, 17, 23, 24]. The applications of PLC controllers is not limited to industrial processes monitoring only but sometimes it is also used in smaller installations particularly wherever it is necessary to adapt the decision

making circuit to specific features of the object or to the requirements of specified process [7,9,17]. Wide scope of possible PLC controllers application as associated with their modular structure. Each PLC controller is equipped with the circuits enabling data acquisition and processing as well as decision making and actuating of controlling systems. Additionally, in order to increase their functional capabilities, PLC controllers are provided with appropriate communication interfaces enabling the connection of large numbers of controllers with each other. Therefore, they are easy to extend and make it possible to perform the assumed control objectives suitably for the existing needs.

Due to their modular construction, the operation of PLC controllers in management system is based on the principle of centralized supervising system with distributed architecture. Each module performs its own control algorithm. The control algorithms of individual modules may be limited to the use for data processing within their own resources only. They may also use their connections with other elements of the system in certain situations determined in their control algorithms. PLC controllers integrated in common structure make it possible to exchange the information about current statuses of inputs and outputs as well as about results obtained from inner processes associated with data processing. The block diagram of an integrated control and supervision system based upon the use of PLC controllers as decision making elements is illustrated in Fig. 1.

The control and supervision processes assumed in working algorithms may be carried out in individual management system modules and may constitute designated structures containing the control, supervision and safety modules.

## THE ESSENCE OF CONTROL AND SUPERVISION SYSTEMS IN THE RESEARCH AND LABORATORY ROOMS

The rooms and objects used for research purpose are specific type of rooms. Often it is necessary to ensure rigorous and precisely determined working conditions in order to achieve the correct flow of research process in such rooms. On the other hand, the proper conditions required to ensure safe work for the personnel is another important aspect of the use of the research and laboratory rooms. Further features of such rooms consist in the possibility of the presence of many various factors, including hazardous factors and factors jeopardizing the human life or health. Also, the essence of a scientific experiment consisting in not completely foreseeable result of the research works contributes to the potential occurrence of certain hazards. Additionally, the research and laboratory rooms may constitute the whole of a building object or only a part of available resources.

From the presented specific features of laboratory rooms it appears that in the case of such rooms:

- it is required to ensure special working conditions in order to enable the correct execution of experiments and scientific studies,
- it is required to ensure correct operation for testing devices and apparatuses as well as measuring equipment,
- it is required to ensure proper working conditions for the operating personnel,
- it is required to ensure special safety measures.

Therefore, the designed and installed control and supervision processes dedicated for the research and laboratory rooms shall anticipate possibility of the presence of various hazardous factors. Said rooms must also have implemented safety procedures to enable automatic responding to hazards identified in the object. These procedures shall be diversified in accordance with various types of hazards. It is important to provide the user with information about the detected hazard sufficient to initiate a correct reaction.

Due to the required features of such objects, their control and supervision systems have to involve not only information transfer procedures but also hazard neutralizing procedures. The functioning of such hazard neutralizing procedure shall anticipate the presence of human factor. The constructive or destructive type is possible in case of human factor occurring in automatic hazard neutralizing procedures. The constructive type occurs in the case of human action aiding the automatic hazard neutralizing process, and the destructive type occurs in the case of human action disturbing this process. Therefore, it is important to

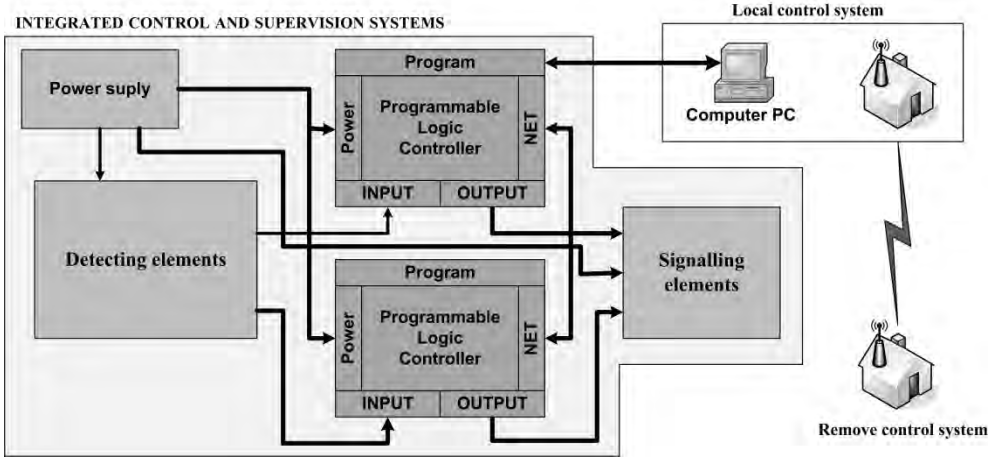


**Fig. 1.** Block diagram of an integrated control and supervision system based upon the use of PLC controller as a decision making unit [own materials]

precisely determine the hazard and to precisely transfer the information about thedetected hazard to the persons who are present in this room or object.

The cooperation of elements performing the tasks of power supply systems, fire protection systems, air-conditioning and lighting systems as well as alarm and access control systems constituting a part of an integrated control and supervision system shall be determined by the hazard detection and neutralizing procedures in the research objects in their operation algorithm.

## THE ROLE OF VOICE WARNING SYSTEMS AIDING THE OPERATION OF SYSTEMS SUPERVISING THE STATUS OF AN OBJECT BEING PROTECTED

The warning system belongs to essential elements of the system supervising the status of an object or area being protected. The task to be performed by the warning system consists in the informing of the occupants of the endangered area about the detected hazard. The warning systems may be characterized by many features, their goals may be achieved by means of various methods and measures. The basic types of warning systems are [1, 4, 12, 13, 16, 17]:

- the hazard warning systems used by the Civil Protection – signals from alarm sirens informing about an air – raid alarm or about land contamination. The system is supported by means of messages broadcast in media,
- the system warning of the approaching privileged vehicle – modulated signal from alarm sirens installed in vehicles. The system is supported by means of red or blue light signals,
- intrusion and hold-up alarm systems – acoustic signal from indoor and outdoor acoustic signalling devices or from optical – acoustic signalling devices,
- acoustic warning systems installed in public utility objects and informing about the detected fire hazard – acoustic signal from *public-address* systems.

The purpose of the presented above warning systems is to perform the warning tasks by generation of a specific alarm signal. This signal is usually generated as a continuous or modulated signal. Its features, duration and broadcasting method contains encoded information about the detected hazard. Generally, such information is knowingly or unknowingly underestimated and often is understood by a limited number of persons only. On one hand, such phenomenon is associated with the specific features of a generated signal (sirens and signals used by the Civil Protection) but on the other hand with a huge number of occurring and frequently repeating in public area of alarm signals originating from alarm systems installed in apartments, shops, offices as well as from automatic alarm systems installed in motor vehicles.

Currently, the warning systems are aided by means of information transfer systems which are new, unknown or expensive at the time of signal entry or standardization. Thanks to technological progress occurred in the scope of information transfer it is possible to apply other more understandable methods of information transfer on local or national or even global level. In the new supervision systems and alarm installations, the acoustic signalling devices are more and more often substituted or additionally aided by means of systems making it possible to transfer the voice commands informing about the detected hazard. Such elements constitute the voice warning systems. The voice warning systems respond to the hazards detected by the control and supervision system installed in the object and inform the system user in an understandable manner about a procedure to be followed in the occurred situation. Most often the voice warning systems are installed in the buildings in order to support the evacuation systems operation (evacuation voice systems) or alarm systems (alarm systems with voice communication).

The task of voice warning systems is to increase the safety of objects occupants in course of performance of the tasks associated with the detected hazard neutralization and to increase the effectiveness of evacuation from the endangered area. These systems may contribute to the reduction of panic frequently occurring in case of chaotic and disordered plan for leaving the area of danger or escaping from the area of danger.

Due to their transparency in the scope of information transfer, the voice warning systems may be successfully used in the special purpose objects e.g. in laboratory rooms. Such objects are often characterized by limited staff, the personnel are highly skilled and trained. However, the number of potential hazard is high and additionally the character of hazards may be different. Therefore, the procedures to be followed in case of hazard may be diversified and certain activities shall be performed in a precise manner. It is possible to transfer the information about the procedures to be followed and about the type of detecteded hazard by means of voice warning systems aiding the control and supervising systems in laboratory rooms.

## CONTROL AND SUPERVISING SYSTEM MODEL – TEST STAND

According to the concept of this article, the authors assumed to build a model and to check the functional capabilities of an integrated control and supervising system dedicated to working processes, information transfer processes and safety assurance processes management in an object incorporating the rooms for research and laboratory purposes. The tasks to be performed by the control and supervising system consists in the performance of processes associated with the control for lighting system, heating system, air – conditioning system, airlock control system, exhaust system, emergency and evacuation lighting system, smoke extract system, firefighting and fire protection system.

The execution of individual actions is associated with the performance of procedures assumed in control algorithm. Said procedures are recorded directly from the computer into programmable logic controllers (PLC) constituting the decision making circuits in the presented control and supervising model. The control and supervising system has

been based on EASY class and MFD class programmable logic controllers (PLC) manufactured by Moeller (Fig. 3). The decision making circuit based on programmable logic controllers (PLC) cooperates with VMG-16 voice messages generators manufactured by SATEL. VMG-16 modules are responsible in the system for generation of relevant messages in voice public address system and in voice reporting system. Relevant messages have been recorded and saved in the memory of VMG-16 voice messages generator. Output system of VMG-16 modules has been provided with loudspeakers for messages listening. It is also possible to control VGM-16 systems operations modes by means of PLC controllers operating in the system as the notification and reporting circuits. Refer to Fig. 2 for the block diagram of an integrated control and supervising system dedicated for laboratory rooms.

In accordance with the block diagram (Fig. 2), apart from PLC controllers, detecting and signalling elements as well as voice messages generators, the model consists of a simulation block and control (intermediate) block. Said blocks make it possible to connect individual alarm sensors and signalling devices as well as to simulate proposed algorithm operation without connecting the real elements to the inputs and outputs.

Thanks to such structure of the integrated control and supervising system model, it is possible to perform the full simulation and to present the system capabilities and functionalities of individual elements of the control and supervising system. It is also possible, as a result of proper model configuration, to perform the assumed scenarios associated with the completion of control process as well as with hazards detection and elimination process in laboratory rooms and with safety procedures checking.

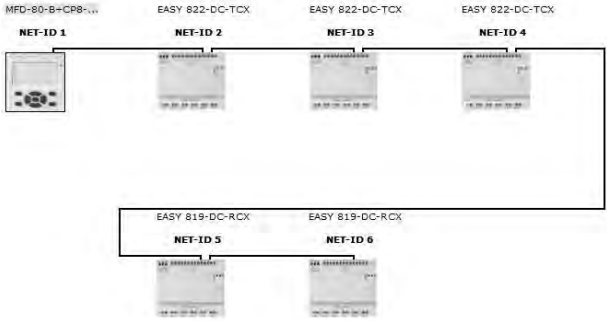


**Fig. 3.** The decision making system structure based on Easy module and on MFD modules [own materials]

The model, as the circuit performing the function of configuration system and the system communicating with the user, contains MFD-Titan controller manufactured by Moeller and consisting of the following subassemblies (Fig. 4): CPU module – MFD-CP8-NT, display module – MFD-80-B, inputs/outputs module – MFD-R16.

The model, as the circuit performing the function of control system, of the supervision system and of alarm system, contains EASY-822-DC-TCX controller (Fig. 5.a) and EASY-819-DC-RCX controller (Fig. 5.b) in order to

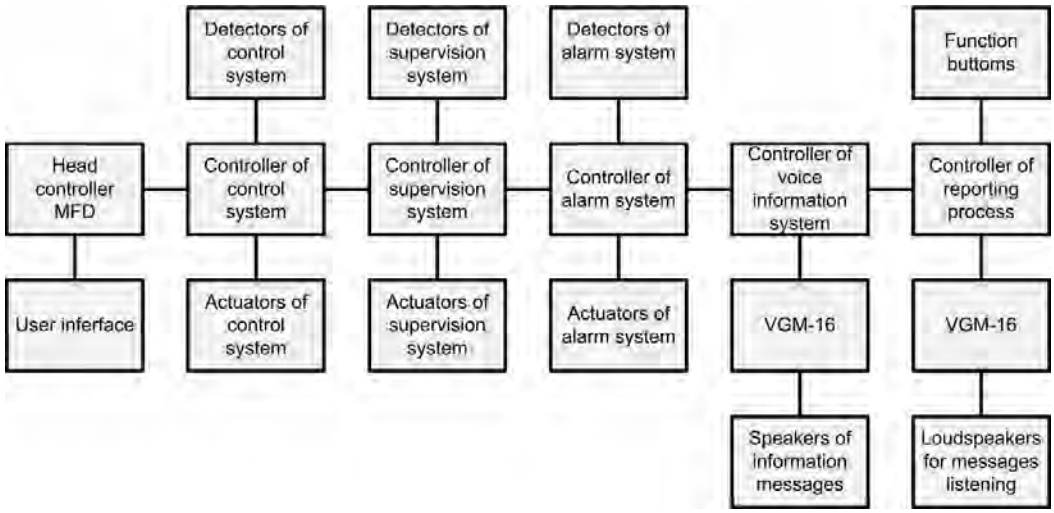


**Fig. 2.** The block diagram of an integrated control and supervising system [own materials]

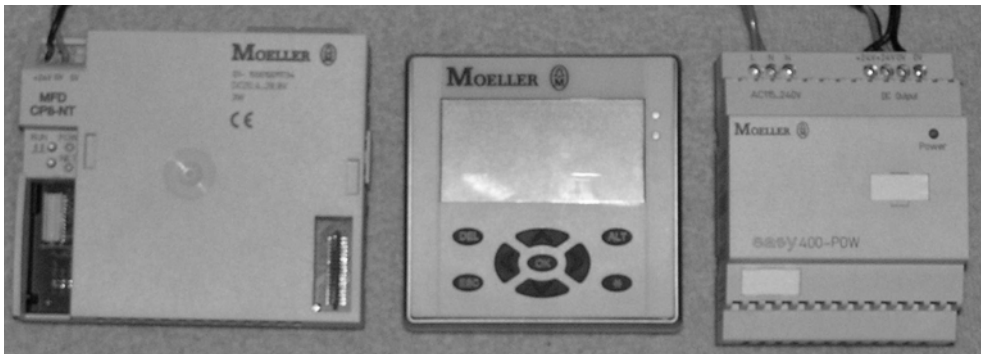


**Fig. 4.** MFD-Titan programmable controller modules [own materials]

perform the functions associated with the management of public address voice system and voice reporting system.

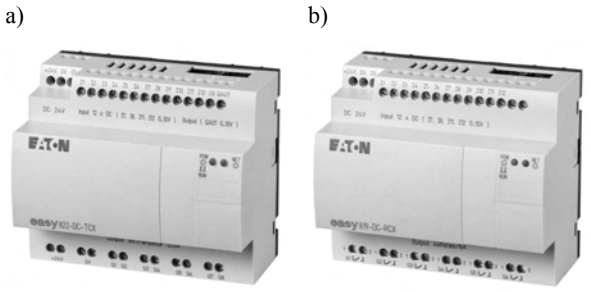


**Fig. 5.** PLC programmable controllers used for the construction of decision making circuit in the control and supervising system model [26]: a) type EASY-822-DC-TCX; b) type EASY-819-DC-RCX

Refer to Fig. 6 for the view of VMG-16 system manufactured by Satel and making it possible to generate prepared voice messages.

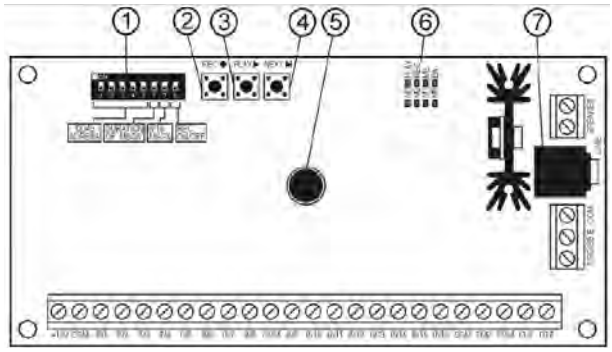


**Fig. 6.** Schematic view of VMG-16 voice messages generator board [25]; 1 – DIP-switch micro-switches assembly, 2 – REC button, 3 – PLAY button, 4 – NEXT button, 5 – microphone, 6 – LED signalling diodes

## SYSTEM OPERATION DESCRIPTION

The operation of the control and supervising system has been verified by means of a few theoretical examples but potentially occurring in real conditions:

1. System reaction to smoke presence,
2. System reaction to the lack of air flow in ventilation duct,
3. System reaction to use of HELP button,
4. Events register review and voice reporting about system status.

The individual elements of the control and supervising system which perform the tasks of this system are responsible for:

– coordination of work of the whole control and supervising system –NET-ID-1 controller – is responsible for the supervision of the correct flow of the whole management process and contains the procedures associated with the supervision of the inner communication between PLC controllers, enabling the communication with the user by means of graphical display,
– the control system –NET-ID-2 controller – is responsible for running the devices included in the laboratory equipment, contains the elements used for controlling by means of buttons and potentiometers,
– the supervising system – NET-ID-3 controller – is responsible for hazards detection in the laboratory rooms and for running the devices neutralizing said hazards, contains the elements used for detection; hazards sensors,
– the alarm system – NET-ID-4 controller – is responsible for the performance of the intrusion and hold-up alarm system tasks; contains detection elements and actuators used in conventional burglary and attack alarm systems,
– the information about hazard – NET-ID-5 controller – is responsible for VMG-16 generator control and public address system control in the laboratory rooms,
– reporting – NET-ID-6 controller – is responsible for VMG-16 generator control and for control of the system loudspeaker used for generation of voice reports informing about the actual object status and about abnormalities detected before.

## CONTROL ALGORITHMS SEQUENCES

### SYSTEM REACTION TO SMOKE PRESENCE

The supervising system (NET-ID-3) consists of smoke sensors as its elements using the resources of binary inputs of this controller (DI1 – DI3). In case of detected smoke presence, the status of signal transmitted to the controller is changed from 1 to 0. This information is interpreted by the controller as an abnormal status and relevant message is sent to the network in the form of properly prepared MB1 byte marker. Said transmitted information is received and interpreted by other controllers. The exhaust fans are started by the control system controller (NET-ID-2). These devices are controlled by means of outputs (DO1-DO2). Simultaneously, the notifying system controller (NET-ID-5) enables the output (DO1) actuating the message (K1) in the generator in order to inform about the occurred hazard in the form of excessive smoke presence.

### SYSTEM REACTION TO THE LACK OF AIR FLOW IN THE VENTILATION DUCT

The initial phase of the event is identical to the system reaction to smoke presence. However, in this case there is no indication of increased air flow on anemometers installed inside ventilation ducts and connected to analogue inputs (AI1-AI2) of the supervising system controller (NET-ID-3). This status is interpreted by the system as the exhaust fans failure. The information about the lack of increased air flow is sent to the controllers network and interpreted in the control system (NET-ID-2) controller. This controller enables the additional fans connected to the outputs of the controller (D03). Due to the operation of additional fans constituting the system reserve, the next message (K2) about necessity to leave the laboratory room is generated as a result of infor-

mation about their operation by means of notifying system (NET-ID-5) controller.

## SYSTEM REACTION TO USE OF HELP BUTTON

The initial phase of the event is identical to the system reaction to the lack of air flow in ventilation duct. However, the further phase is associated with the use of HELP button in order to call for help by the member of personnel inside a smoke – filled room. Help buttons as the alarm system elements use the resources of digital inputs (DI1-DI2) of the alarm system (NET-ID-4) controller. Relevant message is sent by the system to the network in the form of properly prepared MB2 byte marker. The operation of automatic extinguishing system (in case of additional response of fire sensor) is delayed or prevented as a result of proper interpretation of a signal contained in MB2 and a voice message is generated (K3) to inform about the necessity to provide assistance to the occupant in the laboratory room.

## EVENTS REGISTER REVIEW AND VOICE REPORTING ABOUT SYSTEM STATUS

MFD (NET-ID-1) controller coordinates the operation of individual devices and makes it possible to supervise the control process. This controller is provided with proper graphical display creating its own masks. These masks may create a managing application and act as communication interface with the user. It is possible to interpret the actual system status, working conditions in the laboratory and control processes sequence by means of information visible on the display. Relevant messages are generated through the analysis of messages sent from the controllers in the form of markers. The process of ongoing analysis of the system status makes it also possible to generate the messages interpreted by the reporting system controller (NET-ID-6). This controller, using the functional resources including the counters and comparators, creates relevant information byte (MB3) in the memory in order to replay the object status messages saved in VGM-16 generator on request. In case of MB3 status equal to 1, the following message is generated "correct system status, lack of events". The voice message replay is requested by pressing the button connected to DI1 input of NET-ID-6 controller. The pressing will result in the resetting of MB3 byte settings and in the commencement of procedure associated with listening and with updating of MB3 byte parameters for the next report.

## CONCLUSIONS

1. In order to maintain the required and precisely determined working conditions in laboratory rooms and in order to ensure work safety, it is necessary to ensure the constant monitoring for laboratory devices operation and for processes occurring in the research entity. In case of abnormalities, the monitoring system shall be provided with security measures to eliminate the hazard and to enable correct evacuation process for the users.
2. The integrated control and supervision systems with structure based on PLC controllers make it possible to create the complex management systems dedicated for precisely determined working conditions and making it possible to adapt to specific features of the object and its destination. Such systems may successfully perform the role of decision making circuits and data processing systems for the objects with rigorous technical and climatic requirements, i.e. the rooms used for research and laboratory purposes.
3. The systems used for hazard information transfer perform an essential role in safety systems. The correct completion of hazard elimination procedure without exposing the users to unnecessary additional danger is possible only in case of clear and properly transferred information. The voice warning systems have such capability, because they make it possible to communicate information in the form of understandable voice messages.
4. The complete test research demonstrated the suitability of voice messages generators constituting the basic elements of public address system in the laboratory rooms and in scientific – research entities. Such objects are exposed to many different hazards. Such hazards may be diversified in individual rooms. Therefore, the supervising process becomes more complex. The voice messages generators constituting the component of the control and supervising system make it possible to transfer precisely determined information in order to adapt the user's behaviours to the conditions actually existing in the objects.

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## WYKORZYSTANIE GENERATORÓW KOMUNIKATÓW GŁOSOWYCH W ZINTEGROWANYCH SYSTEMACH STEROWANIA I NADZORU W POMIESZCZENIACH LABORATORYJNYCH

**Streszczenie:** Prawidłowa komunikacji systemu z użytkownikiem to ważny przejaw właściwego działania systemu sterowania i nadzoru. Na żądanie użytkownika lub w określonych sytuacjach przekazywana wiadomość powinna precyzyjnie określić stan systemu. W razie wykrycia zagrożenia system zobligowany jest do przekazania użytkownikowi informacji o stanie awaryjnym. Taki sygnał powinien umożliwiać rozpoczęcie procesu neutralizacji zagrożenia lub procesu ewakuacyjnego. Często sygnały o wykryciu zagrożenia przekazywane są za pomocą sygnalizatorów akustycznych lub optyczno-akustycznych. Taki sygnał nie zawiera żadnej informacji o rodzaju wykrytego zagrożenia. Od rodzaju zagrożenia często zależy sposób postępowania w zaistniałej sytuacji. W artykule, na przykładzie pomieszczenia laboratorium chemicznego, przedstawiono współpracę systemu sterowania i nadzoru opartego na układach sterowników programowalnych PLC z generatorami komunikatów głosowych. Zainstalowane w systemie sterowania i nadzoru generatory komunikatów głosowych umożliwiają komunikowanie użytkownika o wykrycia zagrożenia oraz tworzenia raportów głosowych o stanie zabezpieczanego pomieszczenia.
**Słowa kluczowe:** systemy sterowania, systemy nadzoru, generatory komunikatów głosowych, sterowniki PLC

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# Prediction of the Mileage Fuel Consumption of Passenger Car in the Urban Driving Cycle

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**Summary:** Driving cycles obtained when using chassis dynamometer (NEDC, ADAC Eco test) and under real-world driving conditions (CUEDC-P) were initially discussed in the paper. The research aimed at creating a simulation for prediction of mileage fuel consumption based on engine operational parameters, such as fuel consumption and effective power. They were determined for vehicle linear velocities (engine rotational speeds considering respective gearbox ratio) used in the UDC (this test is a sub-cycle of the NEDC test). The next parameter required for the simulation was fuel consumption in neutral gear (designated using engine test bench) and power to overcome resistance to motion. The whole algorithm for argumentation allowed determining the instantaneous fuel consumption for constant and variable velocities and, which is related to this, the simulated mileage fuel consumption. Considering measurement uncertainties, it was higher by 34.8 % to 46 % than the one given by manufacturer and vehicle users.
**Key words:** mileage fuel consumption; instantaneous fuel consumption; passenger car; driving cycles; ECE; UDC; EUDC; NEDC; ADAC Eco test; CUEDC-P.

## INTRODUCTION

The problem of relationships between vehicle fuel consumption under real-world driving conditions and the one obtained as a result of experimental research had already been undertaken at the beginning of the 1970s of the 20th century. It was difficult to make an adequate prediction since properties of the urban traffic of cars depended on a too large number of factors (e.g. driver's driving style, vehicle's technical condition and its rated performance parameters, power transmission system efficiency [8], resistance to motion and fuel physicochemical properties [12]). Nevertheless, when assuming certain simplifications, efforts were made to accomplish this task. The European Driving Cycle, being part of the ECE vehicle regulation, was the Urban Driving Cycle [4, 13] (Fig. 1).

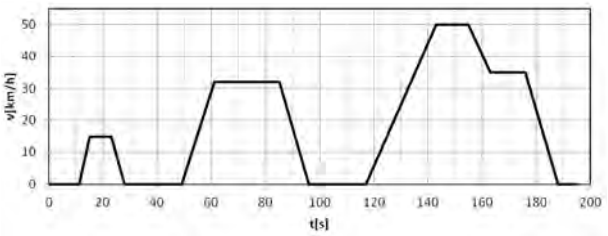


**Fig. 1.** Urban Driving Cycle (UDC) [13]

It is worth noticing that it includes engine operation in neutral gear and vehicle movement both with constant and variable velocities (variable accelerations or decelerations). It is completely possible to be accomplished under chassis dynamometer conditions in order to calculate the mileage fuel consumption based on measurement of the emission of toxic compounds [1,6,18] and is still being used. It is part of the NEDC cycle that consists of fourfold repeated UDC test and a single EUDC test [16].

Hardly reliable representation of fuel consumption according to the NEDC resulted in the development of a certain alternative in the form of the ADAC EcoTest cycle [1, 13]. It was designed in order to evaluate ecologically in an accurate, reliable and objective manner the performance of motor vehicles (testing of mileage fuel consumption using chassis dynamometer and exhaust gas analyser based on CO2 emission) and consisted of 3 tests [1, 13]:

– NEDC cold test (35% of total cycle) – an original is the standard NEDC test on a cold engine with real vehicle mass, instead of generally smaller test weight;
– NEDC hot test (35% of total cycle) – test conditions similar to those in the NEDC cold test but a difference consists in the testing of CO2 emission with warmed up engine and air conditioning turned on onto the set temperature of 293 K;
– ADAC motorway test (30% of total cycle) – this test is designed for a motorway ride at a velocity of 130 km/h.

ADAC EcoTest NEDC cold test allowed obtaining the CO2 emission in 2010 within the range higher by 1% than that reported by the manufacturer, whereas it was lower by 20% in relation to the data reported by users [1, 13].

ADAC EcoTest NEDC hot test showed the CO2 content in exhaust gas in 2010 to be within the range higher by 4% that that reported by the manufacturer, whereas it was 17% lower in relation to the data given by users [1, 13].

Some authors [7,11] determined the mileage fuel consumption based on the emission of carbon dioxide from the following relationship:

$$Q = \frac{CO_2}{k_{CO_2} \cdot 10 \cdot \rho_F}, \quad (1)$$

where:

$Q$ – mileage fuel consumption [dm³/100 km],
$CO_2$ – carbon dioxide emission in exhaust gas [g/km],
$k_{CO_2}$ – coefficient of proportionality for total and complete combustion (= 3.15),
$\rho_F$ – fuel density [kg/dm³].

Another solution, different from fuel consumption testing using chassis dynamometer, was to carry out the driving cycle under real-world conditions. It was called the CUEDC-P (Composite Urban Emission Driving Cycle for Petrol Vehicles), it lasted for thirty minutes and consisted of four sub-cycles: Residential, Arterial, Freeway and Congested. The adopted model assumed the determination of instantaneous fuel consumption based on theoretical formulas as well as on the driving cycle test mentioned above. Very high reliability of the estimation of instantaneous fuel consumption was demonstrated, which was barely different from the values measured in the real-world cycle CUEDC-P [2].

In the available literature, no determinations of mileage fuel consumption according to the driving cycle based on tests performed on an engine test bed have been reported. Usually, they were vehicle "mileages" obtained on the chassis dynamometer, their examples being the NEDC test, ADAC EcoTest or the real-world driving cycle test, i.e. CUEDC-P. Therefore, the author decided to take up this problem based on the standard driving cycle test, i.e. Urban Driving Cycle.

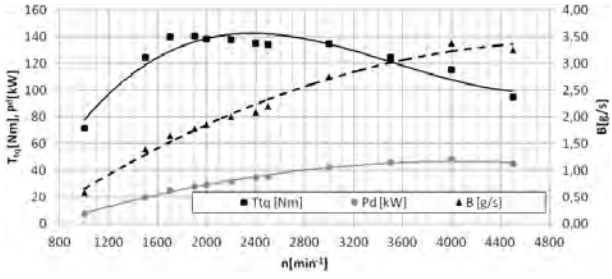


**Fig. 2.** External characteristic of FIAT Multijet 1.3 JTD engine where: **Ttq** – engine torque, **P$^d$** – engine effective power, **B** – fuel consumption, **n** – engine rotational speed

## OBJECTIVE AND METHODS OF EXPERIMENTS

The objective of this study was to make the prediction of mileage fuel consumption for a passenger car equipped with a compression-ignition engine with the Common Rail fuel supply system according to the UDC (Urban Drive Cycle) based on tests. They were made using an engine test bed. Experiments were performed in conformity with the research methods of the piston combustion engine standard PN-ISO 15550 [15] and made according to the requirements specified therein.

The next aspect was to create a simulation that include determination of resistance to motion and calculation of instantaneous fuel consumption under specific motion conditions.

## COURSE OF TESTS

The course of tests consisted in the creation of the external characteristics obtained for FIAT Panda with Multijet 1.3 16V JTD engine (Fig. 2). It was fed with a full dose of ON EKODIESEL fuel with the cetane number 51.1. Ambient parameters during the test were as follows:

– ambient temperature Ta = 294 K,
– ambient pressure pa = 98.5 kPa,
– relative humidity = 40%.

The measured engine torque and its effective power were corrected according to the relations comprised in the normative reference (PN-ISO 15550, [15]).

The points created for torque, effective power and fuel consumption formed characteristic curves as mean values of 4 samples. The procedure consisted in measurements when determining rotational speeds upward and then downward and was repeated twice. For each variable, a trend curve with a high value of the square of the coefficient of correlation ($R^2$) was matched, which was evidence of a good fitting of theoretical and real values. For further simulation, approximated equations of the trend curves for fuel consumption and engine effective power were determined. They were as follows (symbols and their descriptions as under Fig. 2):

a) fuel consumption ($R^2 = 0.9976$):

$$B = -9.6582*10^{-14}n^4 + 1.0324*10^{-9}n^3 - 4.0088*10^{-6}n^2 + 7.5074*10^{-3}n - 3.842, \quad (2)$$

b) engine effective power ($R^2 = 0.9937$):

$$P^d = -4.13301*10^{-6}n^2 + 0.033592345n - 21.64131491, \quad (3)$$

Determination of the resistance to motion and the power required to overcome it as well as the dependence of fuel consumption on

effective power for specific linear velocities required the use of vehicle details and set motion conditions (Tab.1).

**Table 1.** FIAT Panda – basic details and vehicle motion conditions

| variable | value | unit | where: |
|---|---|---|---|
| $M_V$ | 1549 | kg | total vehicle mass |
| $\eta_{PT}$ | 0.9 | - | power transmission system efficiency |
| $r_k$ | 0.270 | m | wheel kinematic radius |
| $c_x$ | 0.3 | - | dimensionless air resistance coefficient |
| $\gamma_P$ | 0.9 | - | fill factor |
| $b_k$ | 1.578 | m | wheel track |
| $H$ | 1.540 | m | vehicle overall height |
| $F$ | 2.190 | m² | vehicle frontal area |
| $f_R^0$ | 0.012 | - | basic rolling resistance coefficient |
| $A$ | 0.00005 | s²/m² | additional rolling resistance coefficient |
| $i_{GI}$ | 3.909 | - | first gear ratio |
| $i_{GII}$ | 2.158 | - | second gear ratio |
| $i_{GIII}$ | 1.345 | - | third gear ratio |
| $i_{FD}$ | 3.438 | - | final drive ratio |

Basic assumptions referring to the selection of values for vehicle details are as follows [3, 16]:
- vehicle was loaded to its permitted gross mass (*MV*),
- power transmission system power efficiency value was adopted as for a passenger car,
- wheel kinematic radius resulted from tyre size (tyre inflated to the pressure being given by manufacturer) and wheel rim taking into consideration static loads during motion,
- fill factor $\gamma_P$ value was adopted as for a passenger car,
- vehicle frontal area was calculated based on the following relationship:

$$F = \gamma_P \, b_k \, H,$$

- basic rolling resistance coefficient *fR*⁰ value was adopted as for smooth asphalt road pavement,
- additional rolling resistance coefficient *A* value was adopted as for most road pavements being applied.

Based on the external characteristics, the values of fuel consumption and engine effective power were specified for the vehicle velocity equal to 15, 32, 35 and 50 km/h used in the UDC. Engine rotational speeds were calculated from the following relationship for vehicle linear velocity [3,16]:

$$v = \omega_w r_k = \frac{2\pi r_k n_w}{60} = \frac{2\pi \cdot r_k \cdot n}{60 i_G i_{FD}}, \quad (4)$$

where:
*v* – vehicle linear velocity [m/s],
*ww*- wheel angular velocity [1/min],
*rk* -wheel kinematic radius [m],
*nw* – wheel rotational speed [min⁻¹],
*n* – engine rotational speed [min⁻¹],
*iG* - gearbox ratio (selectable),
*iFD* – final drive ratio (constant).

After transformation, it was as follows:

$$n = \frac{60 \cdot v \cdot i_G \cdot i_{FD}}{2\pi r_k}, \quad (5)$$

Total power transmission system ratio is as follows [3,16]:

$$i_{PT} = i_G \, i_{FD}. \quad (6)$$

Engine rotational speeds and fuel consumption and effective power values were calculated from Equations (5), (2) and (3).

**Table 2.** Rotational speeds (*n*), fuel consumption (*B*) and effective power ($P^d$)

| gear | *v* | *v* | $i_{PT}$ | *n* | *n* | *B* | $P^d$ |
|---|---|---|---|---|---|---|---|
| | km/h | m/s | - | s⁻¹ | min⁻¹ | g/s | kW |
| I | 15 | 4.17 | 13.439 | 33.01 | 1980 | 1.84 | 28.7 |
| II | 32 | 8.89 | 7.419 | 38.87 | 2332 | 2.10 | 34.2 |
| III | 35 | 9.72 | 4.624 | 26.50 | 1590 | 1.49 | 21.3 |
| III | 50 | 13.89 | 4.624 | 37.86 | 2271 | 2.06 | 33.3 |

## PREDICTION OF MILEAGE FUEL CONSUMPTION AT CONSTANT VELOCITIES

In order to extrapolate the instantaneous fuel consumption, vehicle motion resistances (rolling resistance and air resistance) had to be determined. The first one was determined in the following manner [3,16]:

$$F_R = f_R M_V \cdot 9.81 = f_R^0 (1 + A v^2) M_V \cdot 9.81, \quad (7)$$

where:
$F_R$ – rolling resistance [N],
$f_R$ – rolling resistance coefficient,
$M_V$ – vehicle mass [kg],
$f_R^0$ – basic rolling resistance coefficient,
*A* – additional rolling resistance coefficient [s²/m²],
*v* – vehicle linear velocity [m/s].

Air resistance was described by the following equation [16]:

$$F_A = c_x F p_d = c_x F \frac{\rho v^2}{2}, \quad (8)$$

where:
$F_A$ – air resistance[N],
$c_x$ – air resistance coefficient,
*F* – vehicle frontal area [m²],
$p_d$ – dynamic pressure [N/m²].
$\rho$ – air density [kg/m³],
*v* – vehicle and air (wind) relative velocity [m/s].

Air density was determined from the following relationship [3]:

$$\rho = \frac{0.46 p_b}{T}, \quad (9)$$

where:
$\rho$ – air density [N s² m⁻⁴],
$p_b$ – barometric pressure [1 mm Hg = 133.33 Pa],
*T* – air temperature [K].

When bringing the air density to reference conditions (pressure $pt$ = 100 kPa = 750 mm Hg, temperature $Tr$ = 298 K) the following value was obtained:

$$\rho = \frac{0.46 \cdot p_b}{T} = \frac{0.46 \cdot 750}{298} = 1.16\,[\mathrm{kg/m^3}], \qquad (10)$$

Thus, equation (8) took the following form:

$$F_A = 0.579 c_x F v^2, \qquad (11)$$

Prediction of the mileage fuel consumption was determined based on the value of instantaneous fuel consumption. To determine this value, knowing the value of fuel consumption in neutral gear (Multijet 1.3 JTD engine), fuel efficiency rate and power required to overcome resistance to vehicle motion (FIAT Panda) was required. The process of calculating these functions is presented below.

For example, for the velocity of 15 km/h, it is as follows:

a) fuel consumption in neutral gear a (constant value) was determined from the following relationship [2]:

$$\alpha = B_v = \frac{B_m}{\rho_F}, \qquad (12)$$

where:
$B_v$ – volumetric fuel consumption [dm³/s],
$B_m$ – mass fuel consumption [g/s],
$\rho_F$ – fuel density [g/dm³].

In Table 3 below, fuel consumption in neutral gear was determined.

**Table 3.** Fuel consumption in neutral gear

| $n_{NG}$ | $B_m$ | $\rho_F$ | $B_v$ | $\alpha = B_v$ |
|---|---|---|---|---|
| min⁻¹ | g/s | g/dm³ | dm³/s | mdm³/s |
| 800 | 0.06 | 820.1 | 0.00007 | **0.0731** |

where:
$n_{NG}$ – engine rotational speed in neutral gear.

b) fuel efficiency rate $\beta$ was determined by the following function [2]:

$$\beta = \frac{B_{Cv}}{P_C^d}, \qquad (13)$$

where:
$B_{Cv}$ – volumetric instantaneous fuel consumption [mdm³/s],
$P_C^d$ – engine power corresponding to volumetric instantaneous fuel consumption [kW].

In Table 4, fuel efficiency rate was determined, taking into consideration the data from Table 3.

**Table 4.** Fuel efficiency rate (gear I)

| $n$ | $B_m$ | $\rho_F$ | $B_v$ | $B_{CV}$ | $P_C^d$ | $\beta$ |
|---|---|---|---|---|---|---|
| min⁻¹ | kg/s | kg/dm³ | dm³/s | mdm³/s | kW | mdm³/kJ |
| 1980 | 0.00184 | 0.8201 | 0.002239 | 2.238782 | 28.7 | **0.0781** |

c) power required to overcome rolling resistance and air resistance (determined as an example for the velocity of 15 km/h) [3,16]:

$$P_T = P_R + P_A = F_R \cdot v + F_A \cdot v = (F_R + F_A) \cdot v, \qquad (14)$$

where:
$P_T$ – total power required to overcome rolling resistance and air resistance by vehicle [kW],
$P_R$ – power required to overcome rolling resistance by vehicle [kW],
$P_A$ – power required to overcome air resistance by vehicle [kW],
$F_R$ – rolling resistance [kN],
$F_A$ – air resistance [kN],
$v$ – vehicle linear velocity [m/s].

In Table 5 below, the power required to overcome rolling resistance and air resistance was calculated (resistance to motion was determined based on relationships (7) and (11)).

**Table 5.** Power required to overcome rolling resistance and air resistance

| $v$ | $F_R$ | $P_R$ | $F_A$ | $P_A$ | $F_R+F_A$ | $P_R+P_A$ |
|---|---|---|---|---|---|---|
| m/s | kN | kW | kN | kW | kN | kW |
| 4.2 | 0.179 | 0.75 | 0.01 | 0.028 | 0.2 | **0.77** |

d) instantaneous fuel consumption $fc$ when driving with constant velocity (for v = 15 km/h) was obtained from the following relationship [2]:

$$f_c = \alpha + \beta \cdot P_T = 0.073 + 0.078 \cdot 0.7 = 0.133\,[\mathrm{mdm^3/s}], \qquad (15)$$

e) mileage fuel consumption Q ($v$ = 15 km/h = 4.2 m/s):

$$Q = \frac{f_c}{v} = \frac{0.134}{4.2} = 0.0319\ [\mathrm{mdm^3/m}], \qquad (16)$$

After changing the units from [mdm³/m] to [dm³/100km], the mileage fuel consumption for the constant velocity of 15 km/h amounted to **3.2 [dm³/100 km].**

## PREDICTION OF MILEAGE FUEL CONSUMPTION AT VARIABLE VELOCITIES

The author of this paper has found out that determination of the simulated mileage fuel consumption both for constant velocities (similarly as in section 4) and variable ones, taking into consideration vehicle inertia resistance, was possible.

Instantaneous fuel consumption at variable velocities 15, 32, 35 and 50 km/h was defined in a similar manner as in the case of predicting the mileage fuel consumption at constant velocities, taking into account the value of vehicle accelerations and, which is related to it, vehicle inertia resistance. At the time when vehicle decelerated (negative acceleration value – delay), engine braking (instantaneous fuel consumption equal to zero) and engine running time in neutral gear (after pressing the clutch pedal) were taken into consideration.

Instantaneous fuel consumption at variable velocity (for example for v = 15 km/h = 4.2 m/s and a = 1.04 m/s²) was calculated in the following manner [2]:

$$f_c = \alpha + \beta \cdot (P_T + P_I) + \beta \cdot P_I, \qquad (17)$$

where:
$f_c$ – instantaneous fuel consumption [mdm³/s],
$\alpha$ – fuel consumption in neutral gear [mdm³/s],
$\beta$ – fuel efficiency rate [mdm³/kJ],
$P_T$ – power required to overcome rolling resistance and air resistance by vehicle [kW],
$P_I$ – power required to overcome inertia resistance by vehicle [kW].

Fuel consumption in neutral gear and fuel efficiency rate were determined based on the above-presented relationships in section prediction of mileage fuel consumption at constant velocities a and b, while the power required to overcome rolling resistance and air resistance by vehicle was determined based on Equation (14).

The power required to overcome inertia resistance was determined from relationship [2]:

$$P_I = \frac{M_V \cdot a \cdot v}{1000}, \tag{18}$$

where:
$P_I$ – power required to overcome inertia resistance [kW],
$M_V$ – vehicle mass = 1520 [kg],
$a$ – vehicle acceleration [m/s²],
$v$ – vehicle linear velocity [m/s].

For example for FIAT Panda, it was as follows (a=1.04 m/s², v= 15 km/h= 4.2 m/s):

$$P_I = \frac{1520 \cdot 1.04 \cdot 4.2}{1000} = 6.59[kW]. \tag{19}$$

The value of function (18) allowed determining the instantaneous fuel consumption according to formula (17):

$$\begin{aligned} f_c &= \alpha + \beta \cdot (P_T + P_I) + \beta \cdot P_I = \\ &0.073 + 0.078 \cdot (0.77 + 6.59) + 0.078 \cdot 6.59 \\ &= 1.162 \text{ [mdm}^3\text{/s]}. \end{aligned} \tag{20}$$

Variable instantaneous fuel consumption for variable velocities 15, 32, 35 and 50 km/h at specific vehicle accelerations was determined in a similar manner. In Table 6 above, a simulated instantaneous fuel consumption in the UDC was calculated for respective vehicle motion phase. This was the basis for calculation of aggregate simulated instantaneous fuel consumption (taking into account all phases).

Total simulated mileage fuel consumption was determined from the following relationship:

$$Q = \frac{\sum (f_c \cdot t)}{l} = \frac{7\ .682}{1017} = 0.0764\,, \tag{21}$$

**Table 6.** Simulated instantaneous fuel consumption according to the UDC [13]

| Phase No. | Action | $v_i$ | $v_f$ | $t$ | $t_{sum}$ | $a$ | $f_c$ | $f_c t$ |
|---|---|---|---|---|---|---|---|---|
| | | km/h | km/h | s | s | m/s² | mdm³/s | mdm³ |
| 1 | neutral gear | | | 11 | 11 | | 0.073 | 0.805 |
| 2 | speeding up | 0 | 15 | 4 | 15 | 1.04 | 1.162 | 4.649 |
| 3 | constant velocity | 15 | 15 | 9 | 23 | | 0.134 | 1.202 |
| 4 | braking | 15 | 10 | 2 | 25 | -0.69 | 0.000 | 0.000 |
| 5 | braking, clutch disengaged | 10 | 0 | 3 | 28 | -0.92 | 0.073 | 0.219 |
| 6 | neutral gear | | | 21 | 49 | | 0.073 | 1.536 |
| 7 | speeding up | 0 | 15 | 5 | 54 | 0.83 | 0.955 | 4.773 |
| 8 | gear change | | | 2 | 56 | | 0.073 | 0.146 |
| 9 | speeding up | 15 | 32 | 5 | 61 | 0.94 | 2.114 | 10.572 |
| 10 | constant velocity | 32 | 32 | 24 | 85 | | 0.213 | 5.105 |
| 11 | braking | 32 | 10 | 8 | 93 | -0.75 | 0.000 | 0.000 |
| 12 | braking, clutch disengaged | 10 | 0 | 3 | 96 | -0.92 | 0.073 | 0.219 |
| 13 | neutral gear | | | 21 | 117 | | 0.073 | 1.536 |
| 14 | speeding up | 0 | 15 | 5 | 122 | 0.83 | 1.003 | 5.017 |
| 15 | gear change | | | 2 | 124 | | 0.073 | 0.146 |
| 16 | speeding up | 15 | 35 | 9 | 133 | 0.62 | 1.817 | 16.349 |
| 17 | gear change | | | 2 | 135 | | 0.073 | 0.146 |
| 18 | speeding up | 35 | 50 | 8 | 143 | 0.52 | 2.046 | 16.371 |
| 19 | constant velocity | 50 | 50 | 12 | 155 | | 0.394 | 4.732 |
| 20 | braking | 50 | 35 | 8 | 163 | -0.52 | 0.000 | 0.000 |
| 21 | constant velocity | 35 | 35 | 13 | 176 | | 0.252 | 3.279 |
| 22 | gear change | | | 2 | 178 | | 0.073 | 0.146 |
| 23 | braking | 32 | 10 | 7 | 185 | -0.86 | 0.000 | 0.000 |
| 24 | braking, clutch disengaged | 10 | 0 | 3 | 188 | -0.92 | 0.073 | 0.219 |
| 25 | neutral gear | | | 7 | 195 | | 0.073 | 0.512 |
| | | | | | | | Total | **77.682** |

where:
*vi* – initial velocity, *vf* – final velocity, *t* – phase length, *tsum* – total time of respective phases, *a* – vehicle acceleration, *fc* – instantaneous fuel consumption

where:
$Q$ – mileage fuel consumption [mdm³/m],
$l$ – distance "covered" during the cycle = 1017. [m].

For FIAT Panda, total simulated mileage fuel consumption after changing the units from [mdm³/m] to [dm³/100km] amounted to **7.64** [dm³/100km] and was higher by 41.45 % than real-world mileage fuel consumption (analysis of measurement uncertainties see section 7).

Real-world mileage fuel consumption under determination was based on the type-approval tests according to the guidelines of European Commission Directive 1999/100/EC amounted to 5.4 dm³/100 km in the urban driving cycle [4, 5, 19]. Opinions of the users of vehicles equipped with Multijet 1.3 JTD engine report the same average fuel consumption under urban traffic conditions [14, 17].

## ANALYSIS OF MEASUREMENT UNCERTAINTIES

Table 7 (next page) shows the values of measurement uncertainties (A type standard uncertainty, B type standard uncertainty, expanded standard measurement uncertainty) for the values of fuel consumption obtained in the external characteristics (Fig. 2). They were calculated based on the relationships described in the Guide to the Expression of Uncertainty in Measurement [9]. Expanded standard measurement uncertainties for engine effective power (external characteristics in Fig. 2) were calculated in a similar manner. Table 8 presents the percentage deviations for the observed values. The values of measurement uncertainties for fuel consumption and effective power for the engine rotational speed obtained by approximations used in the UDC are presented below (Tab. 9). Owing to the fact that the values of fuel consumption and engine effective power for the UDC rotational speeds were determined based on the trend curve bit and not measurements, the author of this paper found out that the maximum measurement deviation resulting from two measurement deviations of adjacent rotational speeds had to be adopted for each value. For example, for the rotational speed of 1980 min$^{-1}$, adjacent speeds were 1900 and 2000 min$^{-1}$ with the value of deviations being respectively 1.6 and 1.1 % for fuel consumption and 1.1 and 0.7 % for effective power. Then, a deviation of 1.6% was chosen for fuel consumption and 1.1% for effective power. This was reflected in the ranges of measurement uncertainties for fuel consumption equal to 1.84 ± 0,03 g/s and engine effective power equal to 28.7 ± 0.4 kW.

When assuming the lower value of measurement, mileage fuel consumption was equal to 7.28 dm³/100 km (higher by 34.8 % than real-world mileage fuel consumption), whereas for the upper value of measurement the mileage fuel consumption amounted to 7.88 dm³/100 km (higher by 46 % than real-world mileage fuel consumption).

## CONCLUSIONS

The performed extrapolation of mileage fuel consumption allowed for the following conclusions:

a) mileage fuel consumption determined by simulation according to the reported scheme ranges from 7.28 to 7.88 dm³/100 km (value given be vehicle's manufactures is to 5.4 dm³/100 km);
b) the method included calculation of fuel consumption for the permitted gross vehicle mass; in the chassis dynamometer test, this weight could be lower, hence the lower value of mileage fuel consumption given by manufacturer;
c) the real-world mileage fuel consumption is affected by a great deal of factors not included in this paper or simplified (e.g. variable fuel density, driving conditions – external pressure and temperature, rolling resistance coefficient, tyre inflation pressure, elevations, degree of engine warming up, power transmission system efficiency resulting from changes in the viscosity of gear oils, etc.);
d) fuel consumption according to the type-approval tests carried out when using chassis dynamometer is also loaded by its own error (resulting for instance from inaccuracies of the measuring instruments for emissions of toxic compounds), not given by manufacturer;
e) the UDC is not the best cycle that reflects the simulated mileage fuel consumption in the urban driving cycle for passenger cars being equipped with a compression-ignition engine with the Common Rail fuel supply system;
f) inconsistency of the cycle with the method being assumed results, among other, from high values of accelerations that increase the instantaneous fuel consumption even nine-fold (for example for FIAT Panda: constant $v$ = 15 km/h, constant $f_c$ = 0.134, variable $v$ = 15 km/h, $a$ = 1.04 m/s², $f_c$ = 1.162);
g) the arguments being mentioned allow treating the prediction as an initial one and moving in this research direction in order to possibly modify this method and apply another test than the UDC (or apply its modified version) that will allow reflecting the real-world mileage fuel consumption in the best manner.

**Table 7.** Values of measurement uncertainties for particular engine rotational speeds

| $n$ | $B$ | $u_A(B)$ | $u_B(B)$ | $U(B)$ | B+-U(B) |
|---|---|---|---|---|---|
| min$^{-1}$ | g/s | g/s | g/s | g/s | g/s |
| 1000 | 0.59 | 0.006 | 0.006 | 0.0163 | $0.59 \pm 0.02$ |
| 1500 | 1.39 | 0.007 | | 0.0183 | $1.39 \pm 0.02$ |
| 1700 | 1.65 | 0.016 | | 0.0337 | $1.65 \pm 0.04$ |
| 1900 | 1.78 | 0.009 | | 0.0208 | $1.78 \pm 0.03$ |
| 2000 | 1.85 | 0.005 | | 0.0153 | $1.85 \pm 0.02$ |
| 2200 | 2.01 | 0.003 | | 0.0129 | $2.01 \pm 0.02$ |
| 2400 | 2.08 | 0.046 | | 0.0922 | $2.08 \pm 0.10$ |
| 2500 | 2.20 | 0.007 | | 0.0183 | $2.20 \pm 0.02$ |
| 3000 | 2.75 | 0.009 | | 0.0208 | $2.75 \pm 0.03$ |
| 3500 | 3.08 | 0.012 | | 0.0271 | $3.08 \pm 0.03$ |
| 4000 | 3.38 | 0.004 | | 0.0141 | $3.38 \pm 0.02$ |
| 4500 | 3.25 | 0.010 | | 0.0224 | $3.25 \pm 0.03$ |

**Table 8.** Deviations for fuel consumption and engine effective power

| $n$ | B+- U(B) | $(U(B)/B)$ *100 % | $P^d$+-U($P^d$) | $(U(P^d)/P^d)$ *100 % |
|---|---|---|---|---|
| min$^{-1}$ | g/s | % | kW | % |
| 1000 | $0.59 \pm 0.02$ | 3.3 | $7.5 \pm 0.2$ | 2.7 |
| 1500 | $1.39 \pm 0.02$ | 1.4 | $19.5 \pm 0.3$ | 1.5 |
| 1700 | $1.65 \pm 0.04$ | 2.4 | $24.9 \pm 0.3$ | 1.2 |
| 1900 | $1.78 \pm 0.03$ | 1.6 | $27.9 \pm 0.3$ | 1.1 |
| 2000 | $1.85 \pm 0.02$ | 1.1 | $29.0 \pm 0.2$ | 0.7 |
| 2200 | $2.01 \pm 0.02$ | 1.1 | $31.7 \pm 0.2$ | 0.7 |
| 2400 | $2.08 \pm 0.10$ | 4.8 | $34.1 \pm 0.2$ | 0.6 |
| 2500 | $2.20 \pm 0.02$ | 1.0 | $35.2 \pm 0.2$ | 0.6 |
| 3000 | $2.75 \pm 0.03$ | 1.1 | $42.3 \pm 0.3$ | 0.7 |
| 3500 | $3.08 \pm 0.03$ | 1.0 | $45.6 \pm 0.2$ | 0.4 |
| 4000 | $3.38 \pm 0.02$ | 0.6 | $48.3 \pm 0.2$ | 0.4 |
| 4500 | $3.25 \pm 0.03$ | 1.0 | $44.7 \pm 0.3$ | 0.7 |

where:
$B$ – engine fuel consumption (mean value of 4 measurements), $uA$ – A type standard uncertainty, $uB$ – B type standard uncertainty, $U$ – expanded standard measurement uncertainty

**Table 9.** Values of measurement uncertainties

| $n$ | $n_1$ | $n_2$ | $d_1$ | $d_2$ | $d=max(d_1,d_2)$ | $B$ | $U(B)=Bd$ | $B$-$U(B)$ | $B+U(B)$ |
|---|---|---|---|---|---|---|---|---|---|
| [min$^{-1}$] | [min$^{-1}$] | [min$^{-1}$] | [%] | [%] | [%] | [g/s] | [g/s] | [g/s] | [g/s] |
| 800 | 1000 | 1000 | 3.3 | 3.3 | 3.3 | 0.06 | 0.01 | 0.05 | 0.07 |
| 1980 | 1900 | 2000 | 1.6 | 1.1 | 1.6 | 1.84 | 0.03 | 1.81 | 1.87 |
| 2332 | 2200 | 2400 | 1.1 | 4.8 | 4.8 | 2.10 | 0.10 | 2.00 | 2.20 |
| 1590 | 1500 | 1700 | 1.4 | 2.4 | 2.4 | 1.49 | 0.04 | 1.45 | 1.53 |
| 2271 | 2200 | 2400 | 1.1 | 4.8 | 4.8 | 2.06 | 0.10 | 1.96 | 2.16 |
| $n$ | $n_1$ | $n_2$ | $d_1$ | $d_2$ | $d=max(d_1,d_2)$ | $P^d$ | $U(P^d)=P^d d$ | $P^d$-$U(P^d)$ | $P^d+U(P^d)$ |
| [min$^{-1}$] | [min$^{-1}$] | [min$^{-1}$] | [%] | [%] | [%] | [kW] | [kW] | [kW] | [kW] |
| 1980 | 1900 | 2000 | 1.1 | 0.7 | 1.1 | 28.7 | 0.4 | 28.3 | 31.1 |
| 2332 | 2200 | 2400 | 0.7 | 0.6 | 0.7 | 34.2 | 0.3 | 33.9 | 34.5 |
| 1590 | 1500 | 1700 | 1.5 | 1.2 | 1.5 | 21.3 | 0.4 | 20.9 | 21.7 |
| 2271 | 2200 | 2400 | 0.7 | 0.6 | 0.7 | 33.3 | 0.3 | 33.0 | 33.6 |

where:
$n_1$ – adjacent lower engine rotational speed for which measurements were made, $n_2$ – adjacent higher engine rotational speed for which measurements were made, $d_1$ – measurement deviation for speed $n_1$, $d_2$ – measurement deviation for speed $n_2$, $d$ – maximum deviation selected from among $d_1$ and $d_2$.

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PROGNOZOWANIE PRZEBIEGOWEGO ZUŻYCIA PALIWA SAMOCHODU OSOBOWEGO W CYKLU MIEJSKIM

**Streszczenie.** W artykule wstępnie omówiono cykle jazdy uzyskiwane przy wykorzystaniu hamowni podwoziowej (NEDC, ADAC EcoTest) oraz w warunkach rzeczywistych (CUEDC-P). Celem publikacji było stworzenie symulacji prognozującej przebiegowe zużycie paliwa na podstawie parametrów operacyjnych silnika takich jak: zużycie paliwa oraz moc użyteczna. Wartości tych wielkości zostały wyliczone przy użyciu równań krzywych trendu dobranych do punktów pomiarowych charakterystyki zewnętrznej silnika. Zostały wyznaczone dla prędkości liniowych pojazdu (prędkości obrotowych silnika uwzględniając określone przełożenia skrzyni biegów) wykorzystywanych w cyklu UDC (test ten jest podcyklem testu NEDC). Pozwoliło to na uzyskanie wskaźnika efektywności paliwa dla prędkości 15,32,35, i 50 km/h. Kolejnym parametrem niezbędnym do symulacji było zużycie paliwa na biegu jałowym (wyznaczone przy użyciu hamowni silnikowej) oraz moc potrzebna na pokonanie oporów ruchu. Opory toczenia i powietrza sprecyzowano relacjami wykorzystując dane pojazdu oraz warunki ruchu. Cały algorytm rozumowania pozwolił na wyznaczenie chwilowego zużycia paliwa dla stałych i zmiennych prędkości, a co jest z tym związane, symulacyjnego przebiegowego zużycia paliwa. Uwzględniając niepewności pomiarowe było one od 34,8 % do 46 % wyższe niż to podane przez producenta i użytkowników pojazdu.

**Słowa kluczowe:** przebiegowe zużycie paliwa; chwilowe zużycie paliwa; samochód osobowy; cykle jezdne; ECE; UDC; EUDC; NEDC; ADAC Eco test; CUEDC-P.

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# Motivations and Abilities of Students for Laboratory Classes Aided by Computer Software in English

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**Summary:** The aim of the study was to determine the motivation and abilities of students of five selected fields of study at the University of Life Sciences in Lublin for computer-aided education of Materials Science and Mechanics in English. The tool used for survey was a questionnaire consisting of 17 questions. The questionnaires were anonymously filled by 221 students of the first year. The results showed differences in the declared and actual computer skills in various fields of study. Most students confirmed their interest in the problems of the selection of materials for the products of daily use and the use of computer-aided laboratory classes. However, almost 50% of the respondents are afraid to use a computer program in English.
**Key words:** CES EduPack, computer aided education, Materials Science, Mechanics Science.

## INTRODUCTION

The teaching of technical subjects at the University of Life Sciences cannot be a duplicate of the content and teaching methods used at technical universities. This is due to the different position of this group of subjects in the present study and other attitudes of university students to technical issues. In particular, the teaching of materials, is aiming at preparing students of different fields of study: Agricultural and Forest Engineering (Technika Rolnicza i Leśna – TriL in Polish), Management and Production Engineering (Zarządzanie i Inżynieria Produkcji – ZiIP in Polish) , Transport (Transport – Tr in Polish), Environmental Engineering ((Inżynieria Środowiska – IS in Polish) and Safety Engineering ( Inżynieria Bezpieczeństwa – IB in Polish) to work and to jointly solve the problems with engineers, designers, technologists, and production supervisors. The teaching problems encountered over the years include: continuous lowering of the level of technical knowledge of young people graduating from secondary schools, reduced time for teaching basic technical subjects, increasing size of student groups. The problem of finding proper ways of teaching concerns also computer-aided teaching of Mechanics. To improve the quality of teaching we try to implement modern ways of teaching, based on the results of recent scientific research. Danchenko [3] distinguishes the following main types of educational activities: lectures, labs, workshops, seminars, self-study. He developed the knowledge-based model of decision support system adapted to the task of complex evaluation of e-learning resources quality. A quality education is achieved, inter alia, by varying the interaction of different ways of knowledge transfer: visual, auditory and kinesthetic. This action is based on the results of Dunn et al. [4], Kozielska [8,9] who showed that classes of kinesthetics nature – visual rather than lecture-type result in achieving better learning outcomes, particularly for students of average level or below. Accounting for the sensory preferences of students using Information Technology (IT) is well founded, because it has multichannel influence. The model of adaptive control of the educational process introduced by Tkach [17] consists of optimization of education, forms of organization and conducting classes. The results Cingi [2] and Seker [11] testify to the fact that computer aided instruction improves the efficiency and quality of education; moreover, it is faster and more appealing to students. However, the results of studies conducted by Perbawaningsih [14] in Indonesia show that the use of IT in higher education does not always bring benefits for the learning process. The important reason is the mental attitudes among the leaders of educational institutions, which are associated with organizational policy and students' mental attitudes related to the use of IT. The most well known software in the world in the field of materials science teaching is the package of CES EduPack built by the team of Professor M. Ashby at Cambridge University [6]. Its application for teaching the basics of materials science requires a certain level of students' computer skills and knowledge of English language (as the software is in the English version). The use of CES EduPack software by

students can improve the quality of education among the students of the University of Life Sciences in Lublin. Using the program would allow the broadening of education in ecological but also in economical aspect.

Previous studies on the use of IT by students of the University of Life Sciences in Lublin have shown their good IT skills and widespread use in searching for information on the web. Lorencowicz et al. [10;11;12] and Sołowiej et al. [16] determined, that with years the number of students with access to computers and to the Internet in their place of residence has increased. In their study of 2012 year, they confirmed that 96% of students had their own computers and 97% of students used the Internet in their place of residence [12]. While choosing the major of study **53%** of students suggested the possibility of an attractive employment after graduation. Forty-seven percent of students of TRiL suggested their interests. Comparable results of research are confirmed by Bzowska-Baklarz et al. [1] and Falińska et al. [5]. After the reform of secondary education in Poland, the decrease in the number of students graduating from the secondary technical schools has been noted [5]. At the same time English has become the most popular language of choice at the matura exam in Poland [7].

The purpose of the analysis was to check the motivation and ability of students for learning Materials Science and Mechanics with the application of computer software in English.

## MATERIALS AND METHODS

The research comprised 221 students of the first year: TRiL – 8%, ZiIP – 29%, Tr – 22%, IS – 20% and IB – 22% at the University of Life Sciences in Lublin in 2013. They filled in a questionnaire including 17 questions concerning their level of English, computer skills, motivation to learn Materials Engineering, their opinion of implementation of IT for aided labs, access to computer at home and personal questions. Three of them served as control questions, controlling real computers skills of a student. The questionnaires were anonymous in a paper form. The results of the survey were subjected to statistical analysis using EXCEL software and presented in the form of tables.

## RESULTS

Subjective assessment of students‘ computer skills were rated from 1 to 5, where: 1 – very poor level, 2 – poor level, 3 – medium level, 4 – good, 5 – very good at their computer skills (Table 1).

Fifty-six percent of all students assessed their computer skills as good or very good. Students of TRiL rated their computer skills the highest, 70% of them assessed to be good or very good. The IS students rated their skills the lowest – only 41% of them assessed their knowledge of computer skills as good or very good. The weighted average $\bar{x}$ for each field of study was calculated in the following way:

$$\bar{x} = \frac{\omega_1 x_1 + \omega_2 x_2 + \ldots + \omega_n x_n}{\omega_1 + \omega_2 + \ldots + \omega_n}, \quad (1)$$

where:
*xi* – data set,
*wi* – weight,
*i* – number of test group.

Results for students of TRiL, ZiIP, Tr was 4, for students of IS and IB – 3.

Based on the chi-square test at the significance level of 0.05 we accepted the hypothesis that there is a relationship

**Table 1.** Subjective assessment of computer skills

| Respondents/Major | Score | | | | | Weighted average arithmetic | Rank |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | | |
| Agricultural and Forestry Engineering, TRiL | 0% | 18% | 12% | 52% | 18% | 4 | 1 |
| Management and Production Engineering, ZiIP | 0% | 3% | 33% | 47% | 17% | 4 | 1 |
| Transport, Tr | 0% | 6% | 26% | 48% | 20% | 4 | 1 |
| Environmental Engineering, IS | 0% | 7% | 52% | 39% | 2% | 3 | 2 |
| Safety Engineering, IB | 2% | 10% | 45% | 30% | 13% | 3 | 2 |
| Total | 0.5% | 7.3% | 36.2% | 42.2% | 13.8% | | |

**Table 2.** Correct answers to the questions of computer skills

| Respondents/Major | Correct answers for questions | | | Average | Rank |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | | |
| Agricultural and Forestry Engineering, TRiL | 69% | 82% | 13% | 55% | 4 |
| Management and Production Engineering, ZiIP | 75% | 73% | 38% | 62% | 3 |
| Transport, Tr | 94% | 63% | 42% | 63% | 2 |
| Environmental Engineering, IS | 82% | 50% | 76% | 69% | 1 |
| Safety Engineering, IB | 71% | 43% | 44% | 53% | 5 |
| Total | 79% | 61% | 45% | 62% | |
| CV | 11.5% | 23.5% | 44.6% | | |

between the field of study and subjective assessment of computer skills.

Next, in order to verify the computer skills of students they were asked three questions:

1. Which set of file types is characteristic of computer graphics files?
2. Which website address is incorrect?
3. How can the font be changed to bold?

Respondents were to choose one correct answer from three possibilities: a, b, c. Results of such verification are shown in Table 2.

Only 62% of all respondents correctly answered the questions. The easiest question for them was the first one – 79% of respondents answered correctly, the most difficult – the third one – 45% of correct answers. Only 55% of the students of TRiL gave the correct answers to the questions. Among the students of IS, 69% of them answered correctly. The coefficient of variation was different for each question: the first question – small (12%), the second – average (24%), the third – large (47%) .

This shows that there is a diversity among students in terms of the skills, and the greatest diversity of skills applicable to word processor.

The results of the problem concerning mental attitude of students to computer aided laboratory classes show that seventy-five percent of students would like to learn Materials Science with the help of a computer program. Based on the chi-square test for the significance level of 0.05 it can be considered that there is a relationship between the field of study, and the desire to acquire knowledge of Materials Science with a computer program. The greatest interest in participing in this kind of study was among students of IS – 84% of them and the lowest among students of IB – 60% . Seventy-six percent of respondents believe that the use of computer in the classroom increases their attractiveness. If a computer program was in English, only 30% of respondents would like to take part in such laboratory classes (Table 3).

**Table 3.** Students who want to use a computer program in English to learn Materials Science

| Respondents/Major | Answers | | |
|---|---|---|---|
| | Yes | No | I do not know |
| Agricultural and Forestry Engineering, TRiL | 6% | 53% | 41% |
| Management and Production Engineering, ZiIP | 41% | 45% | 14% |
| Transport, Tr | 25% | 62% | 13% |
| Environmental Engineering, IS | 25% | 48% | 27% |
| Safety Engineering, IB | 35% | 46% | 19% |
| Total | 30% | 50% | 20% |
| CV | 39.6% | 12.3% | 52.5% |

Most volunteers were among the students of ZiIP (41%). Among the students of TRiL only 1 student said „yes“ and 41% of students in this course said „ I do not know“. The coefficient of variation for the answer „no“ is small. It means that the diversity of opinion among students of different fields of study on this issue is small. The coefficient of variation for the answer „I do not know „ and „ yes“ is respectively 53% and 40% . This means that students of different majors have different levels of interest in participating in the activities in which they will use a computer program in English.To test the research hypothesis the chi-square test was performed. At the significance level of 0.05 it can be concluded that among the students of different majors there are different levels of interest in participating in the curse.

Students' fears were related to misunderstanding of their messages, which would be in English. English language as sufficient or worse was assessed by 71% of respondents (Table 4). The worst rating of the level of English was given by the students of Environmental Engineering – 78% of them assessed their knowledge of the English as sufficient or worse, and the best rating was given by the students of Transport – 60%. The weighted average arithmetic for all majors is the same – 3. Based on the chi-square test at the significance level of 0.05, we accepted the hypothesis that there is no relationship between the field of study, and subjective assessment of English.

**Table 4.** Subjective assessment of English knowledge

| Respondents/Major | Score | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| Agricultural and Forestry Engineering, TRiL | 0% | 24% | 41% | 35% | 0% |
| Management and Production Engineering, ZiIP | 5% | 20% | 51% | 19% | 5% |
| Transport, Tr | 0% | 12% | 48% | 38% | 2% |
| Environmental Engineering, IS | 0% | 15% | 63% | 15% | 7% |
| Safety Engineering, IB | 10% | 23% | 38% | 19% | 10% |
| Total | 4% | 18% | 49% | 23% | 6% |

Fourty-eight percent of students believed that the independent search for information, for example about the properties and uses of various materials with the help of a computer program in English could cause them difficulties and discourage participation in the classes. For 42% of the students it could be an additional motivation to learn or help consolidate the knowledge acquired in lectures.

## DISCUSSION

The analysis of the answers to the survey questions indicates that:

1. A majority of the students consider that the most attractive are Materials Science labs aided with the use of various forms of knowledge transfer.
2. The respondents think that the use of the IT increases attractiveness of laboratory classes.
3. The students have their own computers and they use them, but only 60% of respondents answered correctly the questions checking their knowledge of computer skills.
4. The students are interested in properties and applications of engineering materials.

5. Only 30% of students would like to participate in the classes aided by the software in English. This fact is difficult to explain, because English is widely used by majority of computer commands.

We believe that the results of our study point at the advisability of the use of educational software to improve the quality of teaching Materials Science, reducing effort and increasing the speed of acquisition of knowledge by students. Further research activities of the authors should be directed to verification of students' proficiency in English, possible changes in the curriculum aimed at increasing the number of hours of English. Classes can also be carried out for a group of volunteers first and then their opinion on the program and the progress of science could be explored. The results of our research are also useful for improving the effectiveness of teaching in non-technical universities by implementing Working Model, Matlab or other software to teaching Technical Mechanics.

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## MOTYWACJE I PREDYSPOZYCJE STUDENTÓW DO WSPOMAGANIA ZAJĘĆ LABORATORYJNYCH PROGRAMEM KOMPUTEROWYM W JĘZYKU ANGIELSKIM

**Streszczenie.** Celem badań było określenie motywacji i predyspozycji studentów pięciu wybranych kierunków studiów Uniwersytetu Przyrodniczego w Lublinie do komputerowego wspomagania nauczania Nauki o Materiałach i Mechaniki w języku angielskim. Jako narzędzie do badania opinii studentów wykorzystano ankietę złożoną z 17 pytań. W badaniu brało udział anonimowo 221 studentów pierwszego roku studiów. Wyniki badań wykazały zróżnicowanie deklarowanej i rzeczywistej znajomości obsługi komputera na różnych kierunkach studiów, potwierdziły zainteresowanie większości studentów problematyką doboru materiałów na wyroby codziennego użytku i wykorzystaniem komputerowego wspomagania zajęć laboratoryjnych. Jednak około 50% badanych obawia się obsługi programu komputerowego w języku angielskim.

**Słowa kluczowe:** CES EduPack, computer aided education, Materials Science, Mechanics Science.

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# Energy Management in Building Objects Adapted for Users with Reduced Mobility

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**Summary.** Disability is one of essential problems of contemporary world. We can meet disabled people every day in the street in public transport or in shopping centers. However, we do not realize how difficult it is for such people to exist in the world today. The present article is devoted to the integration of electric systems in a modern building adapted for disabled users. In such type of objects it is particularly important to ensure the safety for occupants and property. Selected aspects of safe supply of electricity in hospitals have been discussed and electric devices functioning in course of fire have been described. Furthermore, the article contains the description of a laboratory stand for testing the energy efficient installations of KNX/EIB system to be used for devices management in nursing home rooms with hospital part.
**Key words:** intelligent building, installation, disability, integration, automatic control system.

## INTRODUCTION

Through technological progress, important developments have also taken place in the scope of electrical installations. In recent years there has been more attention paid to rational use of energy. It is a sub-discipline of science constituting an element of essential importance for effective use of energy resources. Alongside with the improvement of building techniques and modern architecture solutions, the electrical installation is also mutating rapidly. Except of its principal purpose i.e. to provide power supply for households, an electrical installation performs the new roles: efforts to save energy, to increase the users' safety and their comfort and to improve its quality [8, 9, 10, 11, 12].

In order to cope with new requirements, there are new building management systems performing the tasks of a conventional installation and introducing many new functionalities making it possible to control individual systems in the building.

Currently, particular attention shall be paid to the optimization of energy consumption. Energy efficiency is a major challenge the contemporary building industry faces. Therefore, the requirements to be met by the building management systems are extremely high, because the awareness in the scope of energy consumption will require to make buildings more cost-efficient. The optimal energy consumption is possible in the building objects equipped with the systems supporting the energy efficiency approach.

## DEFINITION OF A DISABLED PERSON

According to the definition established by the World Health Organization in the year 1980 "a disabled person is an individual with impaired functional ability or life activity that limits or prevents the fulfilment of social roles which are normal for that individual" [4]. This definition has been criticized due to insufficient description of interactions between the individual expectations and abilities as well as the conditions of the society in which he or she lives. Therefore, the aforesaid problem was discussed by European Disability Forum in European Parliament in the year 1994 and the following definition was established: "a disabled person is an individual fully enjoying his/her rights, but handicapped by environmental, economical and social barriers which he/she is unable to overcome like others. These barriers are too often increased by deprecating attitudes manifested by society".

It is impossible to create an universal electric installation suitable for everyone. There are solutions to be applied in case of a person using wheelchair and other solutions dedicated for an individual who is bed-ridden or blind. Therefore, an individual approach is required depending on specific case. The adaptation of public utility buildings is mandatory under applicable building act. Estimated number of disabled persons in Poland corresponds to about 14% of total population, including about 4% with high level of disability and about 100.000 persons using wheelchair.

There are many disability definitions, because it is rather difficult to define this term precisely. Initially, the disability was considered mainly in biological context and a disabled person was defined as an individual who "had the limitations, defects or deficiencies of physical (motor or sensory) or psychological nature" [1]. The following types of disability can be specified:

– moving with the aid of a wheelchair exclusively,
– moving with the aid of crutches, artificial limbs, walking sticks and walking frames,
– blind and visually handicapped,
– deaf and hearing-impaired,
– allergies, phobia and other.

According to the definition established by the World Health Organization "a disabled person is an individual with impaired functional ability or life activity that limits or prevents the fulfilment of social roles which are normal for that individual. Pursuant to the Act issued on 28.06.1997 three degrees of disability were introduced i.e.:

– strong – a person with impaired body ability requiring permanent or long term care and assistance from other persons due to significantly limited possibility of an independent existence,
– moderate – a person with impaired body ability, with ability to perform work on the work station properly adapted to the needs and possibilities resulting from his/her disability, requiring partial or periodical assistance from another person due to limited possibility of an independent existence,
– light – a person with impaired body ability, with ability to perform work, not requiring the assistance from another person,
– hotel guests are particularly the persons from the third and partially from the second disability group. They usually expect the hotel conditions sufficient for normal stay, frequently with family and without emphasized isolation.

In order to understand the required scope of adaptation, it is necessary to thoroughly analyze the anthropometric and ergonomic capabilities of a hotel guest moving with the aid of a wheelchair.

The consideration of visually handicapped persons should be an important element in designing phase in order to create proper floor and wall elements, passages, level differences for them and to intensify the illumination in some sectors. Due to their diseases, the disabled persons are often long term hospital patients. Therefore, energy security is an issue of vital importance to be considered.

## ASPECTS OF ELECTRICITY SUPPLY SECURITY FOR HOSPITALS

The electricity is the most important medium for hospitals and other objects used by health service. Their functioning is influenced in an essential manner even in case of a short term power supply failure. Prolonged interruptions are impermissible. The electricity supply security for the hospital is increased in the form of two levels i.e. through increased reliability of power supply from electric grid and by means of emergency power supply sources. Local energy distribution company is responsible for the first level and the second task is assigned to the maintenance services in the hospital. It is unsafe to use only one transformer for hospital power supply. The technical condition of emergency power supply equipment: Diesel generator units and automatic control elements responsible for generators switching on in case of voltage decay in power supply grid is also an important element in energy security system of the hospital. The electricity demand in hospitals is increased due to the presence of large quantity of medical apparatuses and other technical devices. The emergency generator units are capable to meet only insignificant percentage of real needs in this scope. Therefore, potential overload of emergency generator unit should be taken into account. Frequent accidents are caused by poor knowledge of the users in the scope of safe operation of electric equipment and necessity to ensure uninterruptible operation of hospital facilities [4, 5, 6]. It is necessary to ensure continuous power supply as well as users and patients safety, because electric power supply is required for each electronic device.

It is impossible to ensure any absolute security but exclusively a lower or higher security level. There are the following three factors to be considered in case of analysis of electric security in health care objects:

– electric installation security level,
– security level of electric medical apparatuses,
– security level of use.

When increasing the security level, higher costs should be anticipated but not in a linear manner (Fig. 1) [12]. However, these costs are compensated for by reduced expenditures for elimination of effects of failure and effects of work interruption caused by failure.

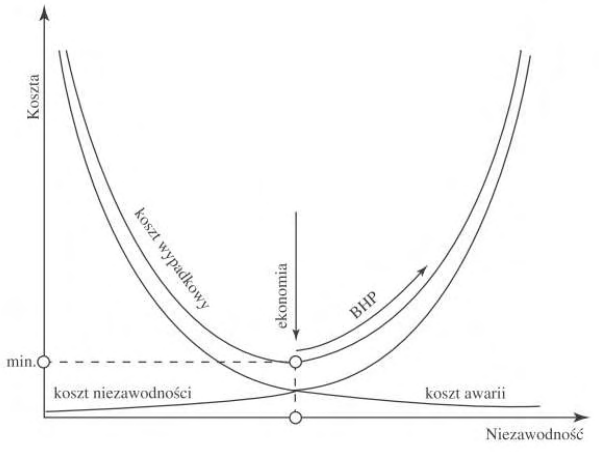


**Fig. 1.** Curve illustrating security costs [12]

For instance the maintenance of operating field lighting, even in case of complete electric power failure in the hospital, makes it possible to complete the operation and to ensure patient's security. The power supply from batteries is turned on automatically in case of voltage decay in power supply grid. The batteries supplying the operating light must not be used for other energy receivers.

The patients are particularly exposed to the risk of electric shock. It is often caused by their disease supporting the flow of electric current and the susceptibility to electric shock.

The following factors contribute to such condition:

– reduction of skin resistance as a result of increased body temperature and sweating,
– difficulties with perception of current flow by the patient, as a result of loss of consciousness, impact of pain killers or anaesthetics, immobilization or permanent connection with electro-medical apparatuses,
– disease load and fatigue.

The whole electric installation in health care objects should be made of copper wires in TN-S system. The steps shall be taken to ensure its compliance with applicable requirements included in the standard [13], as well as in regulation[14].

The range of products proposed by the manufacturers of building management systems encompasses the solutions which are compatible with conventional electric installations and with intelligent systems, which can be dedicated for the use in health service objects [10]. The activities are promoted which lead to the achievement of objectives in the scope of sustainable development. Their scope encompasses energy efficient management in hospitals, care homes and outpatient clinics.

The energy saving in the buildings dedicated for health service uses depends on the awareness of their users who recognize the need to use energy efficient solutions and whose activity contributes to the achievement of energy efficiency. The following actions are also important:

– application of efficient motors and drives, which are often manufactured with economic mode,
– factory assembling of electronic systems enabling more efficient motor control, particularly in case of incomplete loading,
– use of energy efficient agricultural processing equipment in the farms,
– installation of alternative sources of electric energy e.g. wind turbines, photovoltaic panels or heat pumps.

The integration of individual installations is an essential element in the designing of an energy efficient object. Designed station makes it possible to examine interactions between devices installed in a room occupied by a disabled person.

As a result of integration of all the systems existing in the building: heating, air conditioning, ventilation, recuperation, lighting, shutters, it is possible to use energy in an optimal manner and to eliminate mutually excluding functions of the systems e.g. heating and cooling.

In case of system integration in the building it is possible to achieve the real savings in the amount of up to 45% of general costs of the buildings. The devices in the station being the subject matter of the present article are integrated by means of EIB/KNX system.

## ELECRICAL FIRE PROTECTION SYSTEMS

Except of electrical installations providing power supply for energy receivers, the buildings are often provided with the systems responsible for fire safety. The fire protection installation is defined as the system consisting of compatible elements jointly forming a system with determined configuration. In general, they are responsible for the detection of fire hazards as soon as possible, alerts as well as for broadcasting of evacuation signals and messages, for power supply and control of fire protection equipment [11]. Quick detection of fire source gives more time for the completion of building evacuation and for efficient protection of its occupants as well as property accumulated therein. Fire resistant conductors ensuring the functioning of detection and control installations are also used for power supply of electric equipment. In case of electric equipment it became necessary to ensure proper safety level thereof through the use of conductors non – producing any harmful and toxic compounds in course of combustion and through the assurance of functioning of some installations in course of fire [5]. The supply in case of power supply equipment and the use of electric energy receivers is often associated with the release of significant energy losses in that area; most often this energy is converted into thermal energy. In normal operation conditions the thermal energy is transferred to ambient area without causing undesirable significant temperature increase on installations and equipment. The situation is different unless the basic principles are maintained in the scope of correct design, completion and use of installations and equipment. Such installations should be also provided with proper power supply, cables and conductors with proper fastening system. The fire protection master switch is also required in some buildings in order to turn off the power supply for all the receivers excluding the circuits providing power supply for installations and equipment the functioning of which is necessary in case of fire.

## POWER SUPPLY FOR ELECTRIC EQUIPMENT FUNCTIONING IN CASE OF FIRE

The special group of electric energy receivers encompasses the electric devices the functioning of which in case of fire directly contributes to occupants safety in the object; said devices are responsible for early detection and limitation of fire, its propagation as well as hazard data transmission and correct evacuation of occupants from the building under fire [15]. The installations encompassing such devices should be provided with conductors and cables dedicated for functioning in fire conditions and with proper fastening systems. This scope mainly encompasses the following installations [5]:

– fire alarm installation (systems of control, hazard signalling systems),
– back-up and evacuation emergency lighting (solution with central battery),
– sound warning systems (loudspeaker lines, connections between CSP and CDSO when located in different rooms),
– fire fighting equipment (control lines),
– fire fighting ventilation (control functions),
– power supply and control of fire fighting lifts,

– smoke and heat extract equipment (power supply for actuators and control buttons),
– power supply for water pumps for firefighting; chemicals pumps,
– safe shutdown of equipment,
– power supply and control for fire doors and gates.

The devices functioning in aforesaid installation must operate in course of fire; some of them for a shorter period of time, e.g. in case of smoke or heat detector and other for a longer period e.g. in case of smoke extract systems or pumping stations. Part of them does not need any power supply from the grid, because it has been provided with its own emergency power system, e.g. fire alarm system, smoke dampers system or some evacuation lighting systems [10].

Unfortunately the electricity demand is high in case of some devices e.g. mechanical smoke extract systems, fire fighting water pumping stations or lifting devices for rescue teams. The fire protection master switch is also recommended in order to turn off the power supply for all the receivers excluding the circuits providing power supply for installations and equipment the functioning of which is necessary in course of fire.

The building where the voltage decay in power supply grid may create the danger for human life or health, serious hazard for environment as well as significant property losses, should be provided with at least two independent automatically turning on electric energy sources and equipped with automatically turning on emergency (buck-up or evacuation) lighting. A high rise building should be provided with emergency Diesel unit as one of power supply sources [12].

The equipment provided with power supply in course of fire should ensure reliable operation e.g. for 60 minutes the outbreak of the fire in the building. It is directly associated with an alternative power supply system: An alternative power supply system consists of:
– alternative source of electricity,
– alternative cable route i.e. other than the basic route, different cable ducts and shafts, other cable racks and routes in general spaces of the buildings,
– in order to ensure the correct flow of current in fire conditions, the materials and cabling insulation structure of the fastening or racks must be certified for required fire resistance,
– proper cabling cross – sections must selected due to increasing resistance in case of ambient temperature increase.

A frequent error is the transmission of the current from an alternative source of electricity e.g. emergency Diesel unit and from the basic source using the same cabling. This case can be accepted from the power supply failure e.g. substation or power unit but it is unacceptable in case of correct operation of fire-fighting equipment. Therefore the analysis is important for each building [10].

The laboratory stand has been built for testing of intelligent electric installations installed in health service objects and in nursing homes for disabled persons in the Energy Efficient Building Systems Laboratory.

## LABORATORY STAND

The stand can be arranged as a model of hospital room or a room occupied by a disabled person. The stand has been made of acrylic glass (so called plexi) in the form of rectangular prism. The electric installation management is possible thanks to the installation of an intelligent KNX/EIB bus system.

The functioning of KNX/EIB bus system as well as of other intelligent system is based on three types of devices:
1. Sensors – responsible for data acquisition from ambient area; this scope encompasses various sensors i.e. temperature, humidity, smoke sensors etc. but also switches.
2. Actuators – output devices performing determined commands. Their name originates from the fact that their task is to update the statuses of outputs being controlled.
3. Processing devices – the principal system element encompassing the devices processing the information collected by the sensors and controlling the actuators by means of aforesaid information.

The plan of building with actuators arranged thereon (buttons, bulbs, LED controls) is the principal element of the stand. System modules and buttons used for actuators operation are located beneath the plan.

The stand has been completed on the basis of Master Room RM/S 1.1 device. The device has been installed on a mock-up representing the room (Fig. 2). The graphical representation of the room has been provided with diodes as elements signalling the switchover of controller outputs.

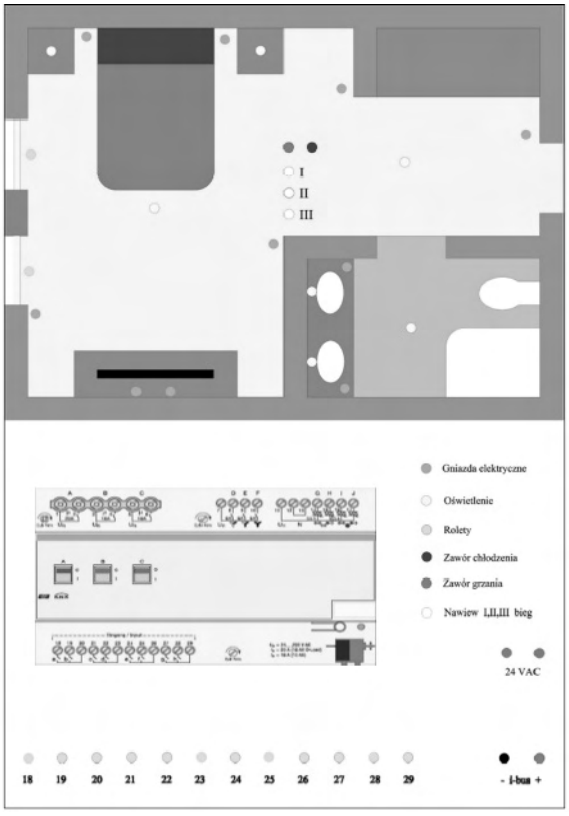


**Fig. 2.** Laboratory stand

The correct operation of the stand is possible when the following conditions are met:
– connection of KNX i-bus (terminals i-bus, +, – ),
– connection of power supply 24VAC actuators end (terminals24VAC),
– connection of sensors (functional buttons etc.) to binary inputs (18-29),
– connection of thermostat RDF/A (element is equipped with temperature sensor and makes possible to control heating, cooling and ventilation functions in local mode),
– correct configuration of Master Room in ETS4 program.

The schematic diagram of controller use on the stand is illustrated in Figure 3. The diodes inform about the active status of lighting elements, heating and cooling valves, shutters opening/closing, electric sockets switching on.

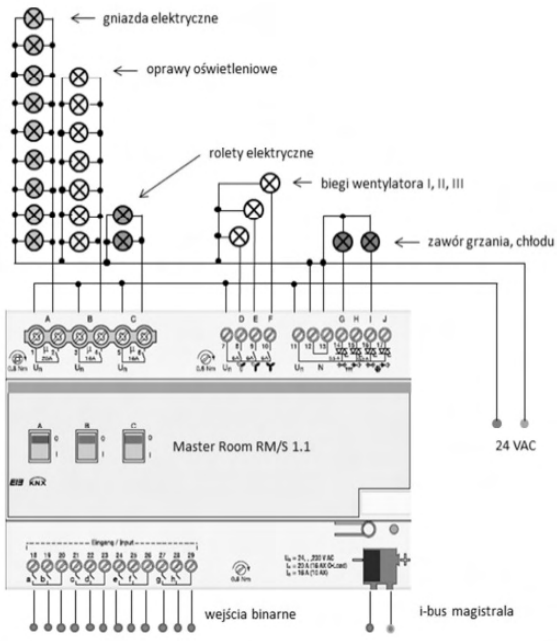


**Fig. 3.** Schematic diagram of energy efficient installation model in a nursing home

Application available in Tebis Visualization utility program is used for intelligent installation operation.

The program is characterized by a simple and user friendly interface and intuitive operation. Therefore its operation is easy even for the user running the program for the first time. Such solutions were applied before in public utility buildings in residential buildings [2, 3].

The scope of program, except its basic function i.e. system elements configuration, encompasses also reports systems for installed elements. The monitoring of current status of devices (device enabled/disabled, button high/low state, number of starts) is possible from the program level.

The elements of KNX/EIB system used in the course of the stand construction represent a complex solution which can be used as the basis for the creation of fully functional intelligent installation. The schematic diagram of the testing stand is illustrated in the figure below.

The stand has been designed in a manner enabling the execution of the basic device functions used in typical room.

The described system makes it possible to control the following elements of the object:
– lighting,
– HVAC installation (Heat, Ventilation, Air Conditioning),
– household appliances & audio/video devices,
– shutters,
– collaboration with alarm/fire protection/access control systems.

Application available in Tebis Visualization utility program is used for intelligent installation operation.

The program is characterized by a simple and user friendly interface and intuitive operation. This feature is particularly important in case of older persons or users with reduced mobility. Such solutions have been applied before in public utility buildings in residential buildings [2, 3].

The scope of program, except of its basic function i.e. system elements configuration, encompasses also reports systems for installed elements. The monitoring of current status of devices (device enabled/disabled, button high/ low state, number of starts, etc.) is possible from the program level.

ETS4 program window with logical structure of the project is illustrated in the drawing presented below.

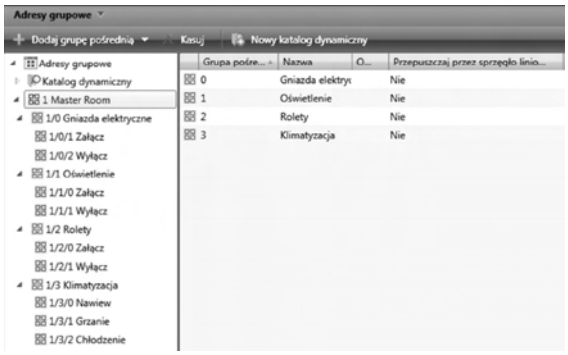


**Fig. 4.** Logical structure of devices management design in nursing home apartment [10]

Figure No 5 illustrates the operation principle in master mode with the devices management aided from dispatching point, e.g. from medical personnel room.

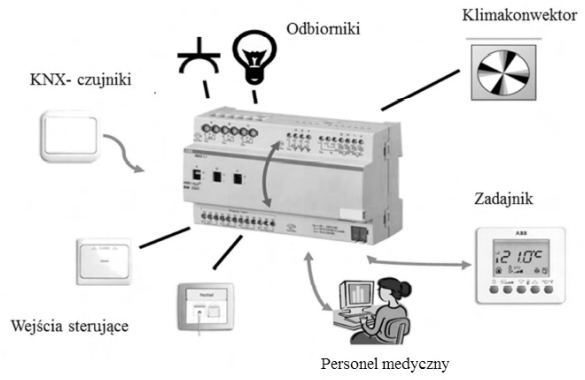


**Fig. 5.** Devices management design in a nursing home apartment

## CONCLUSIONS

In the modern electric installations age with wide spectrum of solutions available on the market, it should be reflected whether to implement such solutions in the buildings dedicated for nursing homes for sick and disabled persons.

The solution presented herein for energy management systems integration in the rooms in a nursing home for disabled persons or in the hospital room is an attempt to implement an energy efficient solution in hospital conditions. This solution can be customized i.e. developed together with increasing needs of its users. The selected KNX/EIB system is the best available building system at the moment. Thanks to its easy installation, components of the system and low power supply voltage of the bus, the patients

staying in hospital or disabled persons living in a nursing home have the possibility to operate the devices in a safe manner. Further extension of installation may consist in the connection of the next actuating modules to existing bus.

The reaction to commands may change depending on the number of modules.

The cost of cabling for EIB/KNX system is about 20 – 30 % higher than in the case of conventional systems and the total cost depends on the building size and the scope of its use. Its undisputable advantage is openness i.e. the possibility to use equipment from different manufacturers and the fact that the system can be extended gradually. In the framework of further works it is possible to extend the stand by next modules and elements in order to increase it functionality. It is possible to add the pushbuttons for the enabling of scheduled actions, sensors detecting lighting intensity or weather making it possible to close or open the shutters automatically.

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## ZARZĄDZANIE ENERGIĄ W OBIEKTACH BUDOWLANYCH PRZEZNACZONYCH DLA OSÓB NIEPEŁNOSPRAWNYCH RUCHOWO

**Streszczenie.** W publikacji poruszono ważną problematykę integracje ze społeczeństwem osób niepełnosprawnych. Zdefiniowano pojęcie osoby niepełnosprawnej. Opisano zastosowanie instalacji inteligentnych w nowoczesnych budynkach przystosowanym dla osób niepełnosprawnych. Omówiono również wybrane aspekty bezpiecznego zasilania szpitali w energię elektryczną oraz urządzenia elektryczne funkcjonujące w czasie pożaru. Ponadto opisano stanowisko laboratoryjne do badania energooszczędnych instalacji systemu KNX/EIB, zarządzających urządzeniami w pomieszczeniach domu opieki z częścią szpitalną.
**Słowa kluczowe:** budynek inteligentny, instalacja, niepełnosprawność, integracja, system automatyki.

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# Comparison of Wind Turbine Energy Production Models for Rural Applications

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**Summary:** The paper presents three models used to estimate energy production of a wind turbine. Methodology to model both wind speed probability and turbine power curve is presented. The results include energy production for four selected turbine types suitable for a small farm and accuracy of various models for average values of wind speed typical for most of the territory of Poland.
**Key words:** wind turbine model, Weibull distribution, Rayleigh distribution, wind energy.

## INTRODUCTION

Wind is a source of energy with relatively great potential over many areas of the world. It originates from the atmospheric air pressure differences. The primary source of it is the solar radiation [13]. Although used already in ancient times, the wind energy has recently gained particular attention as an attractive source of renewable energy [15].

Poland has a moderate potential of wind energy. Only small regions located in the northern part of the country (mostly at the Baltic Sea) have yearly energy density over 2 MWhm$^{-2}$ at 30 m above ground. Approximately 2/3 of the area has wind energy potential between 750 and 1500 kWhm$^{-2}$ (also at 30 m) and is described as quite favorable [16].

In the neighbouring country, Belarus, there are 1840 sites for placing wind energy stations and a potential of 6.5 billion kWh of annual production is estimated [4].

A special attention is paid to renewable sources in the context of agricultural production. Rural areas offer large land availability and farmers can benefit from using renewable energy by using it to supply the energy demand of the farm or selling the excess to the local grid operator. This is an example of the prosumer approach – when the energy producer is also a consumer. Among others, wind turbines are considered as a source of electrical energy suitable for farms and household needs [2][3].

One of the important stages in the investment process is the correct assessment of the energy production and sizing of the turbine for the wind conditions at the planned location. In this context it is essential to use a right model for the turbine energy production.

There are many approaches to the energy production estimation of the wind turbines. Some authors propose sophisticated methods like fuzzy logic and artificial neural networks [12][21], data mining algorithms [14][19] and curve-fitting techniques [5][9]. This paper focuses on the most simple models which can be easily used by farmers to estimate yearly energy production in their location.

## WIND AS A SOURCE OF ENERGY

The wind energy is contained in the kinetic energy of the air particles. The power of the wind stream can be expressed as [9]:

$$P = \tfrac{1}{2}\rho A V^3, \tag{1}$$

where:
$r$ is air density, $A$ – turbine area and $V$ – wind speed.

Not all the energy carried by the air can be withdrawn – in such a case the wind speed behind the turbine would have to be zero which is not possible. The maximum power that can be theoretically extracted from the wind is expressed by the Betz law with limit equal to 16/27 of $P$ defined above [22]. Therefore, the mechanical power delivered by the turbine must meet the following relationship:

$$P_T \leq \tfrac{8}{27}\rho A V^3. \tag{2}$$

The wind speed data can be obtained from various sources. Some of worth mentioning ones are Nasa Atmospheric Science Data Center [17] and Institute of Meteorology and

Water Management – National Research Institute in Poland [11] which provide a web-based tool to obtain historical wind data for a given location.

The wind speed is highly variable in time. On the contrary, the resources, like those mentioned in the previous paragraph, usually provide an average value within a year or month. The power of the wind stream depends non-linearly on the speed, so in order to estimate energy produced by a given turbine it is necessary to know the distribution of the speed values. Usually, for the wind turbine modelling the Weibull distribution is used.

The Weibull distribution of a variable $V$ (in our case the wind speed) can be noted as [18]:

$$\begin{cases} f(V) = \dfrac{k}{c}\left(\dfrac{V}{c}\right)^{k-1} e^{-\left(\frac{V}{c}\right)^k}, V > 0, \qquad k, c > 0 \\ f(V) = 0, \qquad V \le 0 \end{cases} \tag{3}$$

where:
$k$ is a dimensionless shape parameter and $c$ – scale parameter (in ms$^{-1}$ in this case).

When no information about the wind variability is available, the shape parameter $k$ is assumed to be equal to 2 [20] which is usually a good approximation for most of the offshore locations. In such a case the Weibull distribution becomes a Raileygh distribution [18]:

$$f(V) = \frac{2V}{c^2} e^{-\left(\frac{V}{c}\right)^2}, \tag{4}$$

Figure 1 presents the probability density function for three mean values of the wind speed assuming the Rayleigh distribution. As can be clearly seen, the maximum probability has the speed values lower than the mean value, which means that for most of the time the wind speed is lower than the mean value.

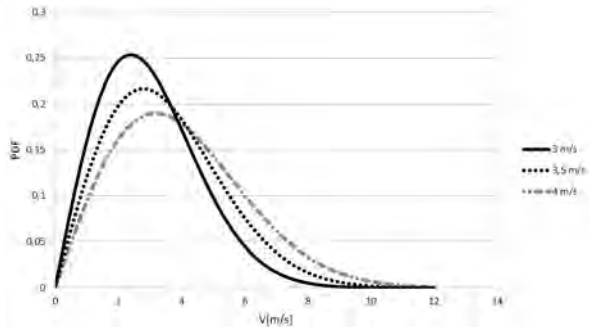


**Fig. 1.** Probability density function for selected values of the mean wind speed assuming Rayleigh distribution.

## WIND TURBINE POWER CURVE MODELS

The turbine manufacturers or research centres usually provide the turbine model in a form of power versus wind speed curve. The spreadsheet files for major international manufacturers are available from the Idaho National Laboratory [10]. Curves for turbines chosen for analysis in this paper are presented in Fig. 2. All the turbines are of Horizontal Axis Wind Turbine (HAWT) type. The presented data are based on resources published by the manufacturers [6] [7][8] or research institute [10].

Another way to simulate the power curve of a given turbine is to approximate it by a polynomial equation, which can be written in many various ways. The turbine power curve can be divided into four sections: zero power (when the wind speed is lower than cut-in speed), wind-depended (approximated by the polynomial), constant (nominal) power (above the nominal power speed) and cut-off section (above the cut-off speed). From the formulas presented in [1] the one combining high accuracy with simplicity and ease of determining the parameters from the power curve is the following quadratic equation:

$$P_T = P_R\left(c_1 V^2 + c_2 V + c_3\right), \tag{5}$$

in which $c_1$, $c_2$ and $c_3$ are coefficients which can be determined from the power curve by fitting the equation to at least three points of data, for example: cut-in speed (power assumed to be 0), nominal power and the corresponding speed and one of the points preferably near the middle of the second section. The fitting can be easily done with help of the LINEST function in the most popular spreadsheet programs.

In order to estimate the energy output of a given turbine it is necessary to calculate the average power and then multiply it by the time $T$ for which the energy needs to be calculated:

$$E = T \int_{V=0}^{V_{\max}} P_T(V) f(V) dV, \tag{6}$$

where:
$f(V)$ is the wind speed distribution function (probability density function). In practice, this equation can be replaced with a sum:

$$E = \sum_{i=1}^{M} P_T(V_i) T(V_i), \tag{7}$$

**Table 1.** The main parameters of the turbines used in the analysis.

| Model | Rated power [kW] | Turbine diameter [m] | Cut-in speed [ms$^{-1}$] | Nominal power speed [ms$^{-1}$] |
|---|---|---|---|---|
| Evance Wind R9000 | 5.0 | 5.5 | 3.0 | 12.0 |
| Bergey BWC Excel-S | 10.0 | 7.0 | 3.0 | 14.0 |
| Zaber ZEFIR D7-P5-T10 | 5.0 | 7.0 | 3.0 | 8.8 |
| Zaber ZEFIR D10-P12-T12 | 12.0 | 10.0 | 3.0 | 9.0 |

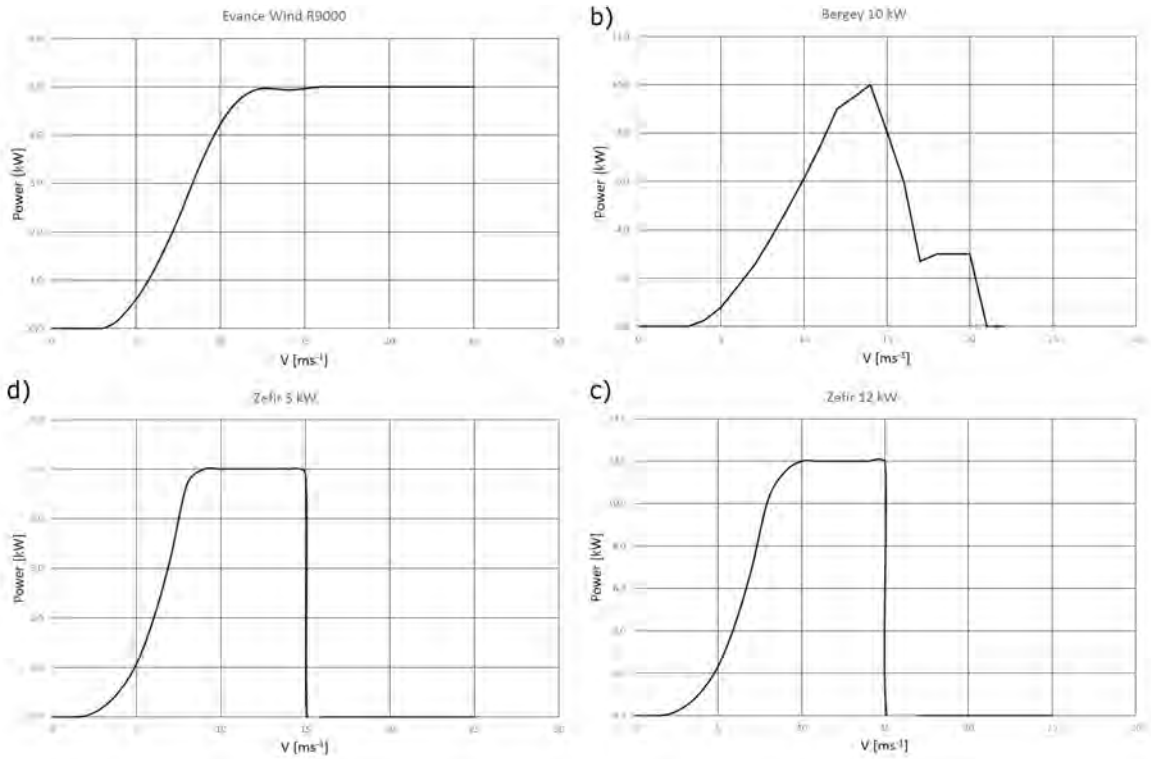


**Fig. 2.** Power curves of sample turbines chosen for analysis: a) Bergey 7.5 kW, b) Bergey 10 kW, c) Zefir 5 kW, d) Zefir 12 kW.

In this formula, the wind speed is divided into $M$ bins $T(V_i)$ in which the wind can be assumed to be constant and equal to $V_i$. For each value of $V_i$ a corresponding power $P_T(V_i)$ and time for which such a speed value occurs in a given period (week, month, year) can be obtained.

The third way to model the energy output is to use a fraction (efficiency) of a total wind energy available. As mentioned earlier, the efficiency cannot be higher than 16/27 but in practice the values of 0.25 or 0.3 can be assumed. In this model, the equation (7) will be changed into:

$$\begin{cases} E = \frac{\eta}{2}\rho A\sum_{i=1}^{M} V_i^3 T(V_i), & V_i > v_{cut-in} \\ E = 0, & V \le v_{cut-in} \end{cases}, \tag{8}$$

where:
$\eta$ is the assumed efficiency, other variables are defined earlier.

## SIMULATION RESULTS

All the three models were implemented in the spreadsheet software. For each model energy production in a 30-day month was calculated for three values of the mean wind speed. The wind speed values were chosen as representative for most of the locations in the Central and Eastern Poland. The results are presented in Table 1, 2 and 3.

The relative errors were calculated with assumption that the energy calculated using the manufacturer's power curve represents the true value:

$$\delta_2 = \frac{E_2 - E_1}{E_1}, \tag{9}$$

$$\delta_3 = \frac{E_3 - E_1}{E_1}. \tag{10}$$

**Table 1.** Energy production (in kWh) in a 30-day month according to different models.

| | $v_{mean}$ = 3 ms$^{-1}$ | | | | $v_{mean}$ = 3.5 ms$^{-1}$ | | | | $v_{mean}$ = 4 ms$^{-1}$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $E_1$ | $E_2$ | $E_3$ | $E_4$ | $E_1$ | $E_2$ | $E_3$ | $E_4$ | $E_1$ | $E_2$ | $E_3$ | $E_4$ |
| R9000 | 208 | 185 | 212 | 270 | 347 | 298 | 340 | 398 | 512 | 441 | 504 | 534 |
| Bergey 10 kW | 292 | 408 | 466 | 340 | 468 | 625 | 714 | 699 | 722 | 906 | 1035 | 952 |
| Zefir 5 kW | 438 | 408 | 466 | 457 | 656 | 625 | 714 | 668 | 899 | 905 | 1035 | 914 |
| Zefir 12 kW | 951 | 832 | 951 | 1003 | 1433 | 1276 | 1458 | 1438 | 1976 | 1848 | 2112 | 1927 |

$E_1$ – Energy calculated using the manufacturer's power curve, $E_2 - E_3$ Energy calculated using eq. 8 (for $E_2$ $h$ =0.35, for $E_3$ $h$ =0.4), $E_4$ – energy calculated using the polynomial approximation of the manufacturer's power curve (eq. 5).

**Table 2.** Relative error of energy production estimation in a 30-day month according to different models.

| | $v_{mean}$ = 3 ms$^{-1}$ | | | $v_{mean}$ = 3.5 ms$^{-1}$ | | | $v_{mean}$ = 4 ms$^{-1}$ | | |
|---|---|---|---|---|---|---|---|---|---|
| | $\delta_2$ | $\delta_3$ | $\delta_4$ | $\delta_2$ | $\delta_3$ | $\delta_4$ | $\delta_2$ | $\delta_3$ | $\delta_4$ |
| R9000 | -0.108 | 0.019 | 0.299 | -0.141 | -0.019 | 0.149 | -0.138 | -0.015 | 0.043 |
| Bergey 10 kW | 0.398 | 0.567 | 0.604 | 0.287 | 0.471 | 0.439 | 0.254 | 0.434 | 0.318 |
| Zefir 5 kW | -0.068 | 0.065 | 0.044 | -0.048 | 0.088 | 0.018 | 0.007 | 0.151 | 0.017 |
| Zefir 12 kW | -0.125 | 0.000 | 0.054 | -0.110 | 0.017 | 0.004 | -0.065 | 0.069 | -0.025 |

$$\delta_4 = \frac{E_4 - E_1}{E_1}. \quad (11)$$

**Table 3.** Average power of the turbines (in kW) according to the power curve based model.

| | $v_{mean}$ = 3 ms$^{-1}$ | $v_{mean}$ = 3.5 ms$^{-1}$ | $v_{mean}$ = 4 ms$^{-1}$ |
|---|---|---|---|
| R9000 | 0.29 | 0.48 | 0.71 |
| Bergey 10 kW | 0.41 | 0.65 | 1.00 |
| Zefir 5 kW | 0.61 | 0.91 | 1.25 |
| Zefir 12 kW | 1.32 | 1.99 | 2.74 |

## DISCUSSION AND CONCLUSIONS

As can be seen from the tables, the results and model accuracy differ depending on the turbine, model chosen and mean wind speed value. For most of the turbines, a simple, efficiency-based model gives acceptable results, at least at the preliminary stage of estimating the energy production. Using the efficiency value of 0.4 the error is kept under 10 % for most of the cases, except for the Berger turbine. As itvcan be seen in Figure 2, the power curve is different from other turbines' curves. Also, despite the rated power of 10 kW, the turbine diameter is 7 m which is equal to the diameter of the 5 kW Zefir turbine. This is why for this type the efficiency-based model is not performing well.

For the polynomial approximation of the power curve, the error is smallest in the case of the Zefir turbines. For the Bergey and Evance Wind the error is high and very high. This is because for the mean wind values simulated, most of the energy comes from a low wind speeds. If the curve is not modelled accurately in this region, the error will be high.

The energy production for the turbines is not very high: the average power (assuming the manufacturers' power curves) is a small fraction of the nominal power. Its values are higher with a higher average wind speed value.

All of the models presented in this paper have the main following limitations:

1) Variation of the air density is not taken into account. The air density changes with temperature, atmospheric pressure and humidity. As the density is one of the factors in eq. 1 it will have an effect on the power generated by the turbine.
2) The assumed theoretical wind distribution (Rayleigh) does not have to be the same as real distribution in a given place. Since the energy production depends highly on the statistical distribution of the wind speed, if the real distribution is different from the ideal approximation, the energy production will be different than the estimation made by any model.
3) The models do not take into account the dynamic states of the turbine.

All the simplified models presented in this paper exhibit considerable errors. It is not possible to choose one of them as one which will perform well for all of the turbines and a wide range of the wind speeds. Therefore, the simple models can be used as a preliminary tool to assess the energy production when no manufacturer data is available and for a more accurate results the power curve data should be used.

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## PORÓWNANIE MODELI WYTWARZANIA ENERGII PRZEZ TURBINY WIATROWE W ZASTOSOWANIACH ROLNICZNYCH

**Streszczenie.** Artykuł przedstawia trzy modele wykorzystywane do modelowania wytwarzania energii przez turbiny wiatrowe. Przedstawiono metodologię modelowania prawdopodobieństwa występowania prędkości wiatru oraz krzywej mocy turbiny. Wyniki obejmują wartość energii wytworzoną przez wybrane typy turbin możliwych do zastosowania w warunkach rolniczych i dla prędkości wiatru typowych dla większości terytorium Polski.
**Słowa kluczowe:** model turbiny wiatrowej, dystrybucja Weibulla, dystrybucja Rayleigha, energia wiatru.

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# Fuel Cells as Energy Storage for Photovoltaic Energy Sources in Rural Areas

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**Summary:** The power produced by many renewable energy sources, like photovoltaic or wind farms, is highly variable over time. In order for the electrical system to be able to receive larger share of energy from these sources some kind of energy storage is needed. The paper presents properties and simple models of PEM fuel cells and PEM electrolysers and evaluation of the possibility of using these devices for energy storage in form of hydrogen production.
**Key words:** smart grid, energy storage, hydrogen production, fuel cells, electrolyser.

## INTRODUCTION

The solar radiation is a highly variable source of energy, as experienced on the surface of the Earth. There are three main causes of this variability. The first one is the yearly travel of our planet around the Sun, which results in differences in the duration of the day, as well as the maximum height of the Sun above the horizon between summer and winter. The second cause is the Earth's daily rotation around its axis. The third source of the radiation intensity variation is of meteorological nature – the cloud presence, the type and thickness play the major role in the energy availability on a given day.

One of the factors which make a wider use of photovoltaics difficult is discrepancy between the time when the electrical energy is needed and when it can be produced: both within a day and year. The problem of energy storage as a supplement to a renewable energy source has been a subject of numerous researches [1, 4, 17, 24]. Apart from conventional ways to store the energy like lead-acid batteries [10] and pumped hydro-storage [15], other methods including super-capacitors [23], flow batteries [7], hydrogen [29] and renewable power methane [21] production are considered.

Many of the rural areas in Europe have an untapped potential for renewable energy sources (RES) [9]. There is a relatively high potential for additional income and unemployment reduction in these areas due to the development of RES. The anticipated transformation of the conventional electrical power network into Smart Grid, among others, includes integration of energy storage devices into the grid [5]. Therefore, energy storage systems will become one more business possibility in the rural areas.

The fuel cells are promising technology in providing high quality power in distributed generation systems (including photovoltaic generation) [11]. The hydrogen generated at times when the generation exceeds power demand can be used in the fuel cells to generate the energy when needed. This approach will provide a way for better balancing the demand with RES.

## FUEL CELLS

Fuel cells are devices which directly convert chemical energy contained in a fuel into electrical energy. One of the most widely used fuel is gaseous hydrogen. In a typical fuel cell the half-reactions can be written as follows [22]:

$$H_2 \rightarrow 2H^+ + 2e^-, \quad (1)$$

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O. \quad (2)$$

The electrons removed on the anode do the work in an external circuit and the proton (the $H^+$ ion) is transferred through some kind of electrolyte (depending on the fuel cell type). On the cathode the proton meets the electrons coming from the circuit and combined with oxygen it forms water. One of the largely used type is the Polymer Electrolyte Membrane Fuel Cell (PEMFC). Its name comes from the construction and material used for the proton – conducting electrolyte. There are many review papers which present various types of fuel cells and their properties like [14, 25, 30].

Figure 1 presents the typical current-voltage curve of a fuel cell with its three main sections illustrated.

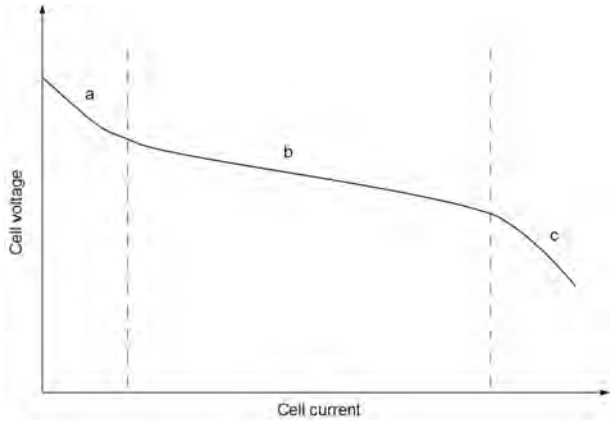


**Fig. 1.** Typical current-voltage curve of a fuel cell: a) activation losses dominant region, b) ohmic losses dominant region, c) concentration losses dominant region.

The fundamental equation which describes the cell voltage $V_{cell}$ is [13]:

$$V_{cell} = E_{Nernst} - V_{Act} - V_{Ohmic} - V_{Con}\,, \tag{3}$$

the cell's reversible (Nernst) potential $E_{Nernst}$ can be calculated as [31]:

$$E_{Nernst} = \frac{1}{2F}\left[\Delta G_e + \Delta S\left(T - T_{ref}\right)\right] + \frac{1}{2F}\left[RT\ln\left(P_H\sqrt{P_O}\right)\right]. \tag{4}$$

Where $DG_e$ – free Gibb's energy, $DS$ – entropy change, $F$ – Faraday constant, $T$ – operating temperature, $T_{ref}$ – reference temperature, $P_H$ – hydrogen partial pressure, $P_O$ – oxygen partial pressure, $V_{Act}$ – activation losses, $V_{cell}$ – cell operating voltage, $V_{Con}$ – concentration losses, $V_{Ohm}$ – ohmic losses, $R$ – gas constant.

In equation (4) the pressures are assumed to be in bars, otherwise each of the pressures should be divided by the value of pressure in standard conditions. Assuming standard pressure and temperature, the above equation can be transformed into [31]:

$$E_{Nernst} = 1.229 - 8.5\times10^{-4}(T - 298.15) + 4.308\times10^{-5}\ln\left(P_H\sqrt{P_O}\right). \tag{5}$$

Activation losses can be calculated using an empirical equation [26]:

$$V_{Act} = -\left(\alpha_1 + \alpha_2 T + \alpha_3 T\ln C_O + \alpha_4 I\right), \tag{6}$$

in which $a_{1...4}$ are empirical coefficients and $I$ is the cell current. The oxygen concentration in the catalytic interface of the cathode $C_O$ can be expressed by[26, 31]:

$$C_O = \frac{P_O}{5.08\times10^6\times e^{-\frac{498}{T}}}. \tag{7}$$

According to Sharifi and others [26]:

$$V_{Ohmic} = I\left(R_P + R_E\right), \tag{8}$$

with resistance for electrons $R_E$ assumed to be constant and small. The resistance for protons $R_P$ is calculated by the classical expression:

$$R_P = \frac{\rho_P L}{A}. \tag{9}$$

The resistivity of the membrane depends on water activity and cell temperature $T$. For Nafion it is expressed by the empirical formula as [8]:

$$\rho_P = \frac{181.6\times\left[1 + 0.03J + 0.062\left(\frac{T}{303}\right)^2 J^{2.5}\right]}{\left(\lambda - 0.634 - 3J\right)e^{4.18\frac{T-303}{T}}}$$

$J$ is the current density within the cell. The value of $l$ can be fitted for a particular cell. Sharifi [26] proposes the following way of obtaining the value of $l$:

$$\begin{cases} \lambda = 0.0045 + 17.81a - 39.85a^2 + 36a^3 & \text{for} \quad 0 < a \le 1 \\ \lambda = 14 + 1.4(a-1) & \text{for} \quad 1 < a < 3 \\ \lambda = 16.8 & \text{for} \quad a = 3 \\ \lambda = 22 & \text{for} \quad a > 3 \end{cases}, \tag{10}$$

where:

$$a = \frac{P_{H_2O,out}}{P_{H_2O}^{sat}}, \tag{11}$$

$P_{H2O.out}$ is the partial pressure of water in the system. The last factor in equation (3) is called concentration losses [12]:

$$V_{Con} = -\frac{RT}{nF}\ln\left(1 - \frac{J}{J_{\max}}\right), \tag{12}$$

The efficiency of the fuel cells is a variable depending on its operating conditions: temperature, current density and rate of fuel delivered and it is reported to be within the range of 20 to 75 % [27].

## HYDROGEN GENERATION

Hydrogen can be produced in many ways. The most popular technology in a large scale production is steam gasification. Its variation is the steam gasification of biomass [20]. For the application of the fuel cell system as the energy storage for renewable sources this technology is not appropriate. A better solution is producing hydrogen by the water electrolysis using the electrical energy from the RES. The advantages include high purity, which is important for the fuelling of fuel cells.

The main technologies used for electrolysis are: solid oxide high temperature [19], alkaline [16] and PEM [6] electrolysers. As an example a summary of a simple PEM electrolyser model will be presented here.

The current – voltage ($I$-$V$) curve of the single cell of an electrolyser can be modelled by the following equation [2]:

$$I = \begin{cases} 0 & \text{for } V \le 1.476\ \text{V} \\ 3.064(V - 1.476) & \text{for } V > 1.476\ \text{V} \end{cases} \tag{13}$$

The hydrogen flow in litres per second can be expressed by [3]:

$$v_H = \frac{RTI}{p2F}, \quad (14)$$

where:
$p$ is the gas pressure and other variables as defined earlier. The relationship (14) can be approximated by a linear expression [2]:

$$v_H = K_H P, \quad (15)$$

in which $K_H$ is a coefficient (equal to 4,1 ml $W^{-1}$ $A^{-1}$ in [2]) and $P$ is electrical power delivered to the electrolyser.

The electrical-to-chemical (hydrogen) energy conversion efficiency is reported around 50 % [2], whereas light-to-chemical efficiency (using photovoltaic generators) is approximately 5 % – mainly due to relatively low efficiency of the photovoltaic generator.

## CONCLUSIONS

Assuming the realistic medium values of energy conversion efficiencies (50 % for electrical energy-to-hydrogen for an electrolyser and 50 % for hydrogen-to-electrical energy for the fuel cells) the overall efficiency in the chain electrical energy from photovoltaic generator – hydrogen production (storage) – electrical energy from fuel cells will be equal to 25 %. This efficiency can be increased by utilising the heat produced both within the electrolyser and the fuel cell and operating as a combined heat and power (CHP) system.

The anticipated evolution of the electrical grid as known today into a smart grid will include, among others, energy storage systems [18]. The decentralised energy storage should be preferably placed in locations which would prevent the need to upgrade the existing electrical grid [28]. One of the available options is storing the energy by the hydrogen production.

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## OGNIWA PALIWOWE JAKO MAGAZYN ENERGII DLA ŹRÓDEŁ FOTOWOLTAICZNYCH W OBSZARACH WIEJSKICH

**Streszczenie:** Moc wytwarzana przez wiele odnawialnych źródeł energii, jak na przykład farmy fotowoltaiczne czy wiatrowe, jest wysoce zmienna w czasie. Aby system elektroenergetyczny mógł przyjąć większą ilość energii z tego rodzaju źródeł konieczne jest zastosowanie magazynu energii. Artykuł przedstawia właściwości i uproszczone modele ogniw paliwowych typu PEM oraz elektrolizerów PEM oraz ocenę możliwości wykorzystania tych urządzeń w celu przechowywania energii w formie wytwarzania wodoru.
**Słowa kluczowe:** smart grid, magazyn energii, wytwarzanie wodoru, ogniwa paliwowe, elektrolizer.

# Comparison of the Quality of Seeding the Virginia Fanpetals Seeds by S071 Kruk Seeder in Laboratory and Field Conditions

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**Summary.** The paper presents the results of the research on the quality of seeding the Virginia fanpetals seeds (*Sida hermaphrodita rusby*) by means of S071 Kruk precision seeder in laboratory and field conditions. It was observed that best quality sowing for the examined classes of distances in a row was obtained at the sowing disk's peripheral speed of 0.23 $m \cdot s^{-1}$ and the working speed of 0.8 $m \cdot s^{-1}$, both in the laboratory and in the field conditions. In subsequent tests a significant impact of the disk's peripheral speed on percentages of single, duplicate and skipped plants was observed. Thus, it can be concluded that the peripheral speed of the sowing disk of the examined seeder impacts the precision of seed distribution in a row.
**Key words:** Virginia fanpetals seeds (*Sida hermaphrodita rusby*), precision seeding, seeding quality.

## INTRODUCTION

Properly performed act of seeding is one of the major factors determining the volume and quality of the yield. Economic justification behind the application of this seeding method is based on the fact that it allows to reduce to a minimum the amount of the sown seeds and thus lower the seeding costs [5, 9, 11].

Sida hermaphrodita rusby, in America commonly known as Virginia fanpetals, was brought to Poland in the fifties of the previous century and since then has been used as a raw material providing energy. This plant belongs to the family of *Malvaceae*. Virginia fanpetals can be reproduced generatively through sowing seeds, but also vegetatively. The growth and development of this plant is basically undisturbed in our climate. Prior to establishing a plantation of this plant, the most advantageous reproduction method should be chosen. It was observed that 1 or 2 year old seeds germinate easily in humid and not crusty soil but the initial growth of seedlings is very slow and the plantation requires intensive weed control [2, 6, 8, 10].

The most frequently applied method of Virginia fanpetals reproduction is sowing seeds, at which it is crucial to properly and carefully arrange individual seeds on a specified unit of surface and keep the same sowing depth for all of them [1, 3, 7, 12, 13].

## MATERIAL AND METHODS

In the laboratory conditions the Virginia fanpetals seeds were sown onto a sticky tape of the research stand.

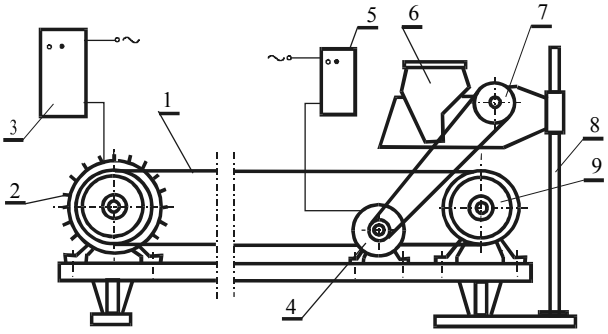


**Fig. 1.** Scheme of the research stand: 1 – sticky tape, 2, 4 – electric engine, 3, 5 – frequency converter, 6 – seed dispensing section, 7 – drive wheel of seed dispensing section, 8 – supporter, 9 – roller straining the sticky tape

Then distances between them were measured on 1-meter measurement sections in 5 repetitions and the percentage of single, duplicate and skipped plants was calculated. Single plants were considered those between which the distance was bigger than half of the average real distance and smaller or equal to 1.5 of the average real distance. Duplicated plants were considered those which grew at distances smaller or equal to the half of the average real distance. Skips were considered at distances bigger than 1.5 of the average real distance.

Then the following values were calculated:
- percentage of single plants expressed as a quotient of the number of single plants and overall number of plants grown on all measurement sections,
- percentage of duplicated plants expressed as a quotient of the number of such plants and overall number of plants grown on all measurement sections,
- percentage of skips expressed as a quotient of the number of skips and overall number of skips on all measurement sections. In the laboratory conditions the precision of seeds distribution in a row was determined [ISO 7256/1-1884 (E) 1984].

In the field conditions the precision of the Virginia fanpetals seeds distribution in a row was determined after the germination process was completed. In order to do that distances between plants were measured on 5-meter measurement sections in 5 repetitions for each peripheral speed of the seeder sowing disk. Classification of the obtained results was carried out following the methodology applied in laboratory research.

**Table 1.** Characteristics of the sown Virginia fanpetals seeds

| Characteristics | Measurement unit | Measurement result |
|---|---|---|
| Length | mm | 2.6 |
| Width | mm | 2.3 |
| Thickness | mm | 1.7 |
| Mass of 1000 seeds | g | 3.4 |
| Germination ability | % | 33.0 |

Geometrical dimensions and weight of 1,000 seeds were determined on the basis of 100 seeds selected at random, measured and weighed. Germination ability was determined on the basis of tests conducted just before proper seeding in laboratory conditions.

The obtained research results were made subject to further statistical analysis based upon a variance analysis and multiple confidence intervals of T-Tukey at an assumed significance level of $\alpha = 0.05$.

## RESEARCH RESULTS

The research results have been presented in the form of charts contained in Figures 2-5 and Tables 2-3.

**Table 2.** Results of testing the quality of sowing Virginia fanpetals seeds with S071 Kruk seeder

| No plot | Peripheral speed of dial (m·s$^{-1}$) | Seeder working speed (m·s$^{-1}$) | The ratio of the average sowing depth to set | Cover seeds with soil (%) |
|---|---|---|---|---|
| 1 | 0.42 | 0.8 | 0.98 | 100 |
| 2 | 0.36 | 0.8 | 0.98 | 100 |
| 3 | 0.23 | 0.8 | 0.98 | 100 |

**Table 3.** Results of testing the quality of sowing Virginia fanpetals seeds with S071

| Seeder working speed (m·s$^{-1}$) | Peripheral speed of dial (m·s$^{-1}$) | Single plants (%) | Duplicated plants (%) | Skips (%) |
|---|---|---|---|---|
| | Laboratory tests | | | |
| 0.8 | 0.42 | 59.9$^{a}$ | 26.5$^{a}$ | 13.6$^{a}$ |
| 0.8 | 0.36 | 67.4$^{b}$ | 27.0$^{a}$ | 5.6$^{b}$ |
| 0,8 | 0.23 | 79.5$^{c}$ | 12.7$^{b}$ | 7.8$^{b}$ |
| | Field tests | | | |
| 0.8 | 0.42 | 35.6$^{a}$ | 42.4$^{a}$ | 22.0$^{a}$ |
| 0.8 | 0.36 | 39.0$^{b}$ | 42.6$^{a}$ | 18.4$^{b}$ |
| 0.8 | 0.23 | 41.6$^{c}$ | 36.8$^{b}$ | 21.6$^{a}$ |

Different letters provided in the indexes mean that at the examined operating speeds of the seeder, significant differences occurred between single and double plants sown and skips at the level of $\alpha = 0.05$

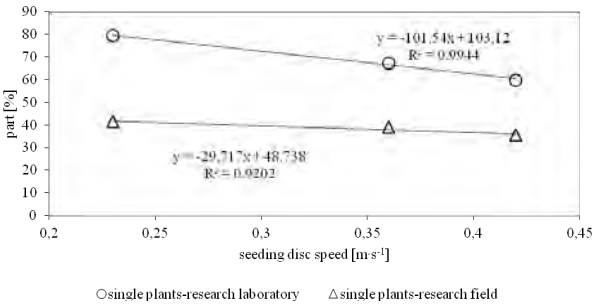


**Fig. 2.** Percentage shares of single plants sown as the function of the Kruk seeding disk speed obtained while sowing the Virginia fanpetals in the laboratory and field conditions

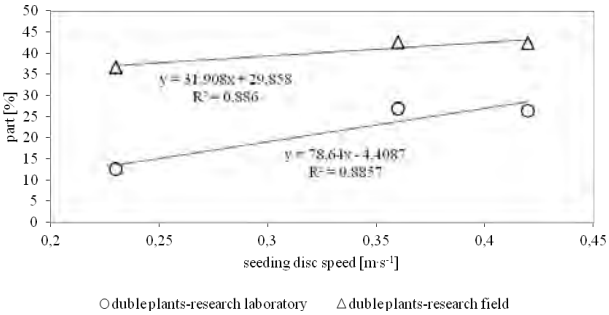


**Fig. 3.** Percentage shares of duplicated plants sown as the function of the S071 Kruk seeding disk speed obtained while sowing the Virginia fanpetals in the laboratory and field conditions

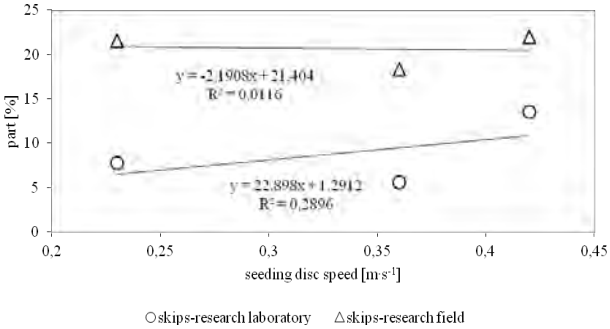


**Fig. 4.** Percentage shares of skipped plants as the function of the S071 Kruk seeding disk speed obtained while sowing the Virginia fanpetals in the laboratory and field conditions

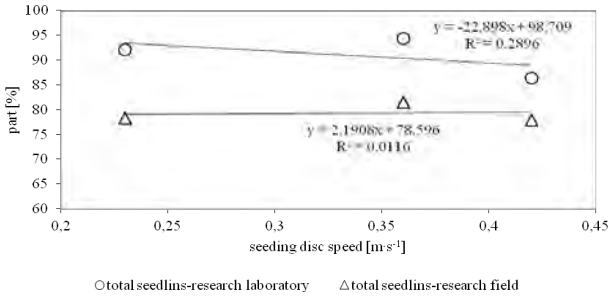


**Fig. 5.** Percentage shares of total seedlings as the function of the S071 Kruk seeding disk speed obtained while sowing the Virginia fanpetals in the laboratory and field conditions

Statistical analysis of the results showed significant differences between the shares of single plants, duplicated plants and skips obtained at the examined seeding disc speed speeds in the laboratory and field conditions.

The trend lines for the shares of single, duplicated and total seedlings, presented in Figures 2, 3, 4 and 5, along with their regression equations, confirm the correlation, which proves that the shares decreased as the peripheral speed of the seeder sowing disk increased.

## CONCLUSIONS

1. Significant influence of peripheral speed of the seeder's sowing disk on percentages of single, duplicate and skipped plants was observed.
2. Negative correlation of simple regression of shares of single, duplicated and skipped seedlings shows that the shares decreased as the peripheral speed of the S071 Kruk seeder sowing disk increased.
3. Most advantageous ratios related to the distribution of the seeds in a row were obtained at the peripheral speed of the sowing disk of 0.23 $m \cdot s^{-1}$.
4. At the examined peripheral speeds of the seeder sowing disk, the ratios indicating the distribution of the seeds in a row obtained in laboratory conditions were better than the ones obtained in the field conditions.

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## PORÓWNANIE JAKOŚCI SIEWU NASION ŚLAZOWCA PENSYLWAŃSKIEGO SIEWNIKIEM S071 KRUK W WARUNKACH LABORATORYJNYCH I POLOWYCH

**Streszczenie.** Przedstawiono wyniki badań dotyczące jakości siewu nasion ślazowca pensylwańskiego siewnikiem S071 Kruk z łyżeczkowym zespołem wysiewającym uzyskane w warunkach laboratoryjnych i polowych. Stwierdzono, że najkorzystniejszy udział nasion i roślin ślazowca pensylwańskiego w badanych klasach odległości w rzędzie wystąpił przy prędkości obwodowej jego tarczy wysiewającej 0,23 $m \cdot s^{-1}$ zarówno w badaniach laboratoryjnych jak i polowych. W próbach stwierdzono istotny wpływ prędkości obwodowej tarczy wysiewającej z łyżeczkami na wielkość procentowych udziałów wysiewów pojedynczych, podwójnych, przepustów i obsiewu całkowitego (suma udziałów nasion wysianych pojedynczo i podwójnie). Zatem można stwierdzić, że prędkość obwodowa tarczy wysiewającej badanego siewnika wpływa na precyzję rozmieszczenia nasion ślazowca pensylwańskiego w rzędzie.

**Słowa kluczowe:** ślazowiec pensylwański, siew precyzyjny, jakość siewu.

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# The Influence of the Kind and the Moisture Content of Straw on its Heating Value

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**Summary.** The goal of the presented research was to determine the influence of the kind and moisture content of straw on its heating value. The research was conducted on four kinds of straw: rape, rye, wheat, and maize straw, and for four moisture levels: 12%, 16%, 20% and 26 %. The results show that the highest heating value has been obtained for rape straw, and the heating value for rye straw is insignificantly lower. Maize and wheat straw reveal significantly lower heating value than rape straw. Additionally, this research has proven that the heating value decreases with increasing moisture content of straw.
**Key words:** straw moisture content, heating value

## INTRODUCTION

Biomass is one of numerous renewable energy sources, and both its big energetic potential and ecological effect speak for its energetic exploitation. This is because the pollution (carbon dioxide) emission to atmosphere during the combustion of biomass is practically equal to zero [21, 2, 23, 10].

According to Miciuła [16] ecological, economic and social benefits resulting from utilizing biomass include:

- Decreased emission of substances having damaging effect on the environment including sulfur dioxide, nitrogen oxides and organic contamination,
- Reduction of carbon dioxide emission, responsible for the greenhouse effect (correlation with the amount of burned biomass),
- Limitation of environment degradation resulting from fossil fuel mining and the depositing biomass-type waste in the environment,
- Exploitation of energetic potential of biomass,
- Development of local labor markets,
- Development of numerous sectors of economy,
- Increase of energetic safety of the country.

Heat is obtained as a result of biomass burning, and this heat can be processed into other types of energy, e.g. electric energy. Besides, burning biomass leaves 4 times less ash than burning other solid fossil fuels which can be used as fertilizer [1, 4, 5, 11, 19].

Vegetable unprocessed biomass reveals relatively low bulk density, which influences transport and storage costs, as well as practical use. Therefore, the increase of the biomass concentration and energy through briquetting and pelleting significantly increases the comfort of distribution and use of this biofuel [6, 7, 12, 13, 18].

Straw is the basic vegetable resource for briquette or pellet production. After the required amount of straw is used for bedding, fodder, and incorporation into soil by plowing, the surplus of straw can be successfully applied for briquette or pellet production [3, 8, 9, 20, 22].

According to Hejft [9] and Niedziółka et al. [17] the energetic value of vegetable biomass depends on the kind and condition of the raw material and on its moisture content in the first place. This is, because high contents of water decreases the amount of heat arising during biomass burning, thus decreasing its heating value and increasing pollution emission.

## MATERIALS AND METHODS

The experiments were conducted for four kinds of straw (rape, rye, wheat and maize) and for four moisture content levels: 12%, 16%, 20% and 26 %.

The determination of the moisture content of straw was performed using the oven-dry method, according to the procedure described in norm [PN-93/Z-15008/02]. The measurement of the moisture content of the materials was carried out in 5 repetitions and defined by the following formula (1):

$$W = \frac{m_o - m_1}{m_o} \cdot 100 , \qquad (1)$$

where:
$W$ – moisture content of the examined material (%),

$m_0$ – mass of material sample prior to drying (g),
$m_1$ – mass of material sample after drying (g).

The determination of the heat of combustion was performed following the procedure described in [PN-ISO 1928]. The heating value was calculated based on combustion heat determined by means of KL-12 Mn. The measurement of combustion heat of the examined materials was carried out in 3 repetitions.

The obtained results were analyzed from the statistical point of view using the SAS Enterprise Guide 5.1. program. The results of the statistical analysis are shown in the variance analysis tables containing appropriate averages along with specification of their impact on important differences between the examined features. Significance level $\alpha = 0.05$ was assumed in all these analyses.

## THE RESEARCH RESULTS

Figure 1 presents the mean heating values of the examined kinds of straw depending on their moisture content. While analyzing the obtained research results, it was identified that along with the decrease of the materials' moisture content from 26 to 12%, the highest growth of the heating value occurred in case of the maize straw (ca. 23%), much lower increase occurred for the rape straw (ca. 14%) and the lowest one for the rye straw (11.4%) and the wheat straw (10,6%).

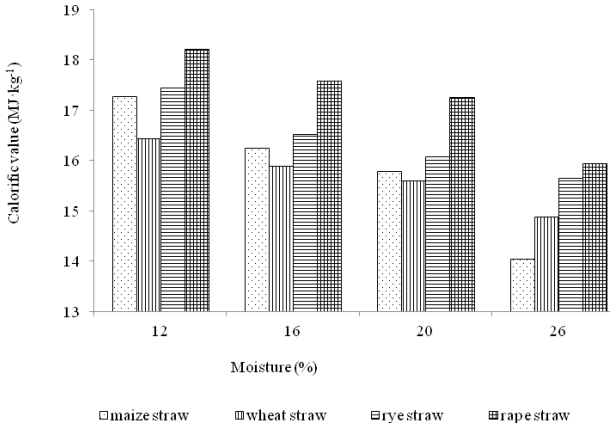


**Fig. 1.** Average heating values of the investigated straw kinds depending on their moisture content

In order to investigate the influence of the straw kind and moisture content on the heating value, two-way analysis of variance was performed and interactions between factors were investigated. The obtained results are shown in Table 1. The obtained coefficient of determination was $R^2$ =0.72. Table 1. shows that the heating value of straw largely depends on its kind and the moisture content; on the other hand, no important influence on the heating value could be ascribed to the interaction of the kind and moisture. Thus, we may say these parameters were not strongly dependent on each other.

**Table 1.** Analysis of variance for the straw heating value depending on the kind of straw and its moisture

| Source of variability | df | SS | MS | Value $F_0$ | $P(F > F_0)$ |
|---|---|---|---|---|---|
| Kind of straw | 3 | 17,79 | 5,93 | 9,48 | 0,0001 |
| Moisture | 3 | 30,34 | 10,13 | 16,19 | <0,0001 |
| Kind*Moisture | 9 | 3,20 | 0,36 | 0,57 | 0,8120 |
| Error | 32 | 20,02 | 0,63 | - | - |
| Whole thing | 47 | 71,40 | - | - | - |

In order to investigate which straw species and moisture content value influences the heating value most, Tukey's test was performed, i.e. pairs of means were compared. The obtained results are shown in Table 2.

**Table 2.** Simultaneous comparisons of heating value of Tuckey for the examined kinds of straw and moisture

| Heating value ($MJ \cdot kg^{-1}$) | Kind of straw | | | |
|---|---|---|---|---|
| | Rape | Rye | Maize | Wheat |
| Average values | $17,239^{A}$ | $16,412^{AB}$ | $15,826^{B}$ | $15,696^{B}$ |
| Moisture | 12% | 16% | 20% | 26% |
| Average values | $17,332^{A}$ | $16,549^{AB}$ | $16,170^{B}$ | $15,122^{C}$ |

Averages with the same letter do not significantly differ at the significance level of $\alpha = 0,05$

We can conclude from Table 2 that the highest heating value (17.239 $MJ \cdot kg^{-1}$) was obtained for rape straw. However, no significant difference was indicated between the heating values of rape and rye straw. Maize and wheat straw reveal significantly lower heating value than rape straw. There was no significant difference between the heating values of maize and wheat straw.

We can also conclude from Table 2 that moisture content also influences the heating value of straw. The straw of the lowest investigated moisture content (12%) demonstrated the highest heating value. Additionally, significant differences between the straw heating values for 12% moisture content and both 20% and 26% moisture content were obtained. No significant differences were obtained between the straw heating values for 12% and 16% moisture content, nor 16% and 20%. Significantly, the lowest heating value was obtained for 26% moisture content straw.

In sum, we can conclude that the highest heating value was obtained for rape straw, slightly lower value was obtained for rye straw, and significantly lower values were obtained for maize and wheat straw. The heating value decreases with increasing moisture content of straw within the investigated material. This confirms the results obtained by other authors [9, 18].

## CONCLUSIONS

The obtained results and their statistical analysis lead to the following conclusions:

1. The experiments showed that both straw species and moisture content significantly influence the straw heating value.
2. The highest heating value (17.24 MJ·kg$^{-1}$) was obtained for rape straw. However, no significant difference was found between the heating values of rape and rye straw (16.55 MJ·kg$^{-1}$). Maize and wheat straw demonstrate significantly lower heating value.
3. Moisture content is an important factor influencing the heating value of straw. The highest heating values were obtained for the straw of 12% and 16% moisture content, and no significant difference was found between them. The straw of 26% moisture content demonstrates significantly lower heating value.

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## WPŁYW RODZAJU I WILGOTNOŚCI SŁOMY NA JEJ WARTOŚĆ OPAŁOWĄ

**Streszczenie.** Celem pracy było określenie wpływu rodzaju i wilgotności słomy na jej wartość opałową. Badania przeprowadzono dla czterech rodzajach słomy (rzepakowa, żytnia, pszenna i kukurydziana) oraz czterech poziomów ich wilgotności (12, 16, 20 i 26%). Badania wykazały, że najwyższą wartością opałową charakteryzowała się słoma rzepakowa, nieistotnie niższą – słoma żytnia oraz istotnie niższą w porównaniu do słomy rzepakowej – słoma kukurydziana i pszenna. Stwierdzono również, że wraz ze wzrostem wilgotności słomy jej wartość opałowa ulegała obniżeniu.

**Słowa kluczowe:** słoma, wilgotność, wartość opałowa.

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# Pressure Compaction of Sugar Beet Pulp – Process Parameters and Quality of the Agglomerate

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**Summary:** This paper presents the results of analyses investigating the effect of moisture content (10 to 22%) and the addition of the binder such as molasses (5%) and calcium lignosulphonate (2%) on the compaction parameters of sugar beet pulp. The experiments were performed with the use of the ZWICK Z020/TN2S universal strength tester and a closed compression die assembly. An increase in moisture content led to an increase in material density in the compression chamber and agglomerate density (by 28% on average). The lowest energy outcomes were noted during compaction of sugar beet pulp without content of binder (average 17,71 J·g$^{-1}$), and the highest ones during compaction of sugar beet pulp with addition of the molasses– at about 23,53 J·g$^{-1}$. The agglomerated sugar beet pulp with addition of the calcium lignosulphonate, at the moisture of 19%, was shown to have the highest value of mechanical strength of about 2.2 MPa.
**Key words:** compaction, sugar beet pulp, moisture content, binder, calcium lignosulphonate, LignoBond DD, molasses.

## INTRODUCTION

The main direction of utilization of sugar-beet pulp is to use it in the feeding of farm animals [2, 5]. In this case the sugar pulp is to be preserved by acidification or drying. Subsequently, the dried pulp can be subjected to briquetting or pelleting. This form is the most convenient for transport and feeding [3, 10].

However, due to the observed decrease in livestock populations and rapidly growing market of biomass [1, 13, 18, 19], an alternative direction to use the compacted pulp may be its assignment for energy purposes. During the manufacture of pulp pellets, molasses may be added in an amount from 5 to 15%. As a result, on the one hand the energy value of the product increases, on the other hand the addition of molasses favors the formation of agglomerates with high mechanical strength. Molasses is used mainly by sugar mills producing feed pellets. However, for energy purposes, due to possible technical difficulties, molasses can be replaced by the addition of lignin binders [14, 17, 20], what results in improved viscosity of processed material. as well as reduced sensitivity of formed agglomerates to humidity changes. Hence, there is a possibility of agglomeration of material at higher moisture without the risk of decreasing mechanical durability of the final product.

During compacting of plant biomass its moisture plays a fundamental role [4, 11 , 12, 15] . Inadequate moisture can lead to losses in energy consumption and results in the formation of agglomerate with inadequate strength properties. In earlier works the results of studies on the influence of moisture and addition of binders on the efficiency of compaction of biomass of various origins were presented [6, 7]. This work is a continuation of the research in this field. Hence, the aim of the study is establishment of parameters characterizing the compaction process of sugar-beet pulp (with the addition of binders) at different moisture contents.

## MATERIALS AND METHODS

The experimental material was sugar beet pulp from the sugar factory "Krasnystaw". The raw material 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 the equation for mass change over time based on the following dependence:

$$m_1 = m_0\left(\frac{100 - w_0}{100 - w_1}\right) \text{ (g)}, \qquad (1)$$

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 – LignoBond DD and molasses) was added to material samples with various moisture content as the calcium lignosulphonate

(amount of 2%) and the molasses (amount of 5%). Material without the binder served as the control. The research materials prepared in this way for the purposes of further analysis are marked as: sugar beet pulp without the binder – $Z_l$=0%; sugar beet pulp plus calcium lignosulphonate – $Z_l$=2%; sugar beet pulp plus molasses – $Z_l$=5%.

The pressure compaction methodology was described in the authors' previous study [8]. The experiment was performed with the use of 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. The test parameters were as follows: mass of material sample – 2 g, cylinder (compacted material) temperature – 20ºC, piston speed – 10 mm·min$^{-1}$, maximum unit piston pressure – 113 MPa. Every compaction process was performed in three replications.

The results were plotted on a compaction curve showing the correlation between compaction force and piston speed. The curve was used to determine the maximum material density in the chamber $\rho_c$ and total compaction effort $L_c$. The coefficient of susceptibility to compaction $k_c$ ($k_c = L_c' \cdot (\rho_c - \rho_n)^{-1}$ was calculated, where: $L_c' = L_c \cdot m^{-1}$ – specific compaction effort, $m$ – weight of material sample, $\rho_n$ – initial bulk density of the raw material. The agglomerate density after 48 of storage ($\rho_a$) was determined.

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 $\rho_n$ ($S_{zm} = \rho_c \cdot \rho_n^{-1}$, $S_{za} = \rho_a \cdot \rho_n^{-1}$). The mechanical strength of a briquette $\delta_m$ was determined in the Brazilian compression test using the Zwick Z020/TN2S tensile testing machine (with piston speed of 10 mm·min$^{-1}$). The 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 [9, 16]:

$$\sigma_n = \frac{2F_n}{\pi\, dl} \text{ (MPa)}, \qquad (2)$$

The correlations between the moisture content, the binder content of the examined material and compaction parameters were analyzed in the STATISTICA program at a significance level of $\alpha_i = 0.01$.

## RESULTS

Regression equations describing the correlations between compaction parameters, the moisture content in the experimental material and the binder content are presented in Table 2. The regression analysis revealed that the studied correlations can be described by a quadratic equation of the second degree or logarithmic equation. The analyzed correlations are presented in Figures 1-4.

### DENSITY OF MATERIAL IN THE CHAMBER AND BRIQUETTE DENSITY

From the test results shown in Figure 1, it is evident that for each studied material the increase in moisture content resulted in increased density of the material in the chamber, $\rho_c$. Additionally, higher moisture caused a decrease in differences in the values of the parameter $\rho_c$, depending on the type of material being processed. However, in the case of density of agglomerate $r_a$, the largest density increase was observed at moisture content ranging from 10 – 16%. In turn, a further increase of moisture practically did not influence the density of the agglomerates obtained from the pulp with the addition of binders. At 16 and 19% of moisture the values of agglomerate density were not statistically different ($p > 0.01$). Likewise, agglomerate density proved to be statistically insignificant and upon the nature of

**Table 1.** Regression equations describing the correlations between density $\rho_c$, $\rho_a$, compactive effort $L_c'$, coefficient $k_c$, degree of compaction $S_{zm}$, $S_{za}$, and mechanical strength $\delta_m$, moisture content $w$, binder content $Z_l$, and the values of determination coefficient $R^2$

| Feature | Binder content | Regression equation | $R^2$ |
|---|---|---|---|
| Density of material in the chamber, $\rho_c$ | $Z_l$=0% | $\rho_c = 0{,}431 \ln w + 0{,}473$ | 0,891 |
| | $Z_l$=2% | $\rho_c = 0{,}303 \ln w + 0{,}865$ | 0,897 |
| | $Z_l$=5% | $\rho_c = 0{,}243 \ln w + 1{,}061$ | 0,927 |
| Density of agglomerate after 48 h., $\rho_a$ | $Z_l$=0% | $\rho_a = -0{,}006w^2 + 0{,}201w - 0{,}599$ | 0,853 |
| | $Z_l$=2% | $\rho_a = -0{,}004w^2 + 0{,}131w - 0{,}037$ | 0.951 |
| | $Z_l$=5% | $\rho_a = -0{,}004w^2 + 0{,}14w - 0{,}088$ | 0,878 |
| Compression work, $L_c'$ | $Z_l$=0% | $L_c' = 0{,}103w^2 - 5{,}035w + 69{,}9$ | 0,998 |
| | $Z_l$=2% | $L_c' = 0{,}056w^2 - 3{,}411w + 60{,}46$ | 0,993 |
| | $Z_l$=5% | $L_c' = 0{,}056w^2 - 3{,}244w + 60{,}19$ | 0,995 |
| Coefficient of susceptibility to compaction, $k_c$ | $Z_l$=0% | $k_c = 0{,}143w^2 - 6{,}128w + 72{,}38$ | 0,995 |
| | $Z_l$=1% | $k_c = 0{,}108w^2 - 4{,}922w + 63{,}39$ | 0,998 |
| | $Z_l$=2% | $k_c = 0{,}085w^2 - 4{,}098w + 57{,}31$ | 0,992 |
| Degree of compaction of material, $S_{zm}$ | $Z_l$=0% | $S_{zm} = -0{,}015w^2 + 0{,}538w + 1{,}822$ | 0,967 |
| | $Z_l$=2% | $S_{zm} = -0{,}015w^2 + 0{,}363w + 3{,}571$ | 0,954 |
| | $Z_l$=5% | $S_{zm} = -0{,}007w^2 + 0{,}256w + 4{,}618$ | 0,958 |
| Degree of compaction of agglomerate, $S_{za}$ | $Z_l$=0% | $S_{za} = -0{,}024w^2 + 0{,}76w - 2{,}005$ | 0,848 |
| | $Z_l$=2% | $S_{za} = -0{,}015w^2 + 0{,}529w - 0{,}033$ | 0,831 |
| | $Z_l$=5% | $S_{za} = -0{,}014w^2 + 0{,}497w + 0{,}146$ | 0,932 |
| Agglomerate mechanical strength, $\delta_m$ | $Z_l$=0% | $\delta_m = -0{,}011w^2 + 0{,}422w - 2{,}831$ | 0,983 |
| | $Z_l$=2% | $\delta_m = -0{,}014w^2 + 0{,}495w - 2{,}424$ | 0,978 |
| | $Z_l$=5% | $\delta_m = -0{,}012w^2 + 0{,}431w - 1{,}873$ | 0,936 |

the binder used (calcium lignosulfonate 2 % or 5% molasses). However, during compaction of beet-pulp without addition of binders, in the range of 16-22% moisture a sharp decrease in the density of the final product occurred. In each experiment higher values of the analyzed parameters were characteristic for the pulp with binder. Parameter $\rho_c$ ranged from 1.42 to 1.79 g·cm$^{-3}$ and parameter $\rho_a$ from 0.83 to 1.2 g·cm$^{-3}$.

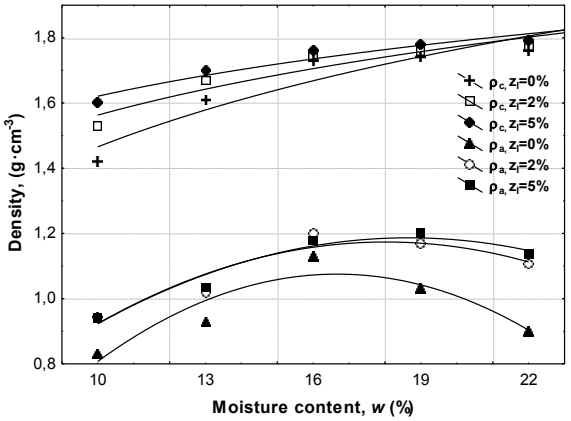


**Fig. 1.** Correlation between material density in the chamber ($\rho_c$), agglomerate density ($\rho_a$) and moisture content ($w$) at various binder content levels ($z_l$)

## DEGREE OF AGGLOMERATE COMPACTION

Changes in the degree of compaction of the material in the chamber and the agglomerate after storage are illustrated in Figure 2. For all materials tested the highest values were found at 16% of moisture content, and the smallest at moisture of 10%. The maximum density of the material in the chamber, ρc for the application of 16% moisture content is on average 6.7 times higher than the initial density material $\rho_n$, regardless of amount of binder addition. It should also be noted that at higher moisture contents, differences in the degree of compaction resulting from type of raw material diminished.

The highest compactions level of the agglomerate $S_{za}$ were achieved for pulps with addition of binders and compacted at moisture 16 and 19%. In such processing conditions the density of agglomerate was about 4.5 times of the initial pulp density.

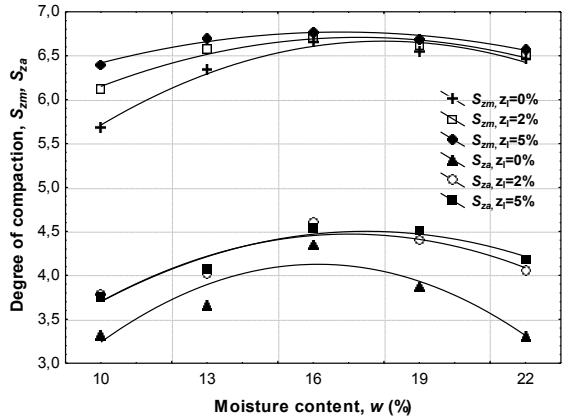


**Fig. 2.** Correlation between the degree of material compaction *($S_{zm}$)*, agglomerate compaction ($S_{za}$) and moisture content ($m$) at various binder content levels ($z_l$)

## COMPACTION EFFORT AND SUSCEPTIBILITY TO COMPACTION

Data presented in figure 3 show that the increasing of moisture content of beet pulp resulted in an increase of its ability to compaction. Probably, due to the increase of water content material becomes more soft (plastic), and consequently the energy inputs required for its compaction decreases. The value of the specific work of compaction $L_c$' ranged from 9.23 to 33.87 J·g$^{-1}$. The highest values of the energy were obtained for the pulp containing 5% of molasses, and the smallest for the pulp without addition of binders. It can be assumed that addition of binders caused an increase of the coefficient of internal friction of the material particles as well as the increase of friction of the die wall. Consequently, this led to the increased inputs of specific compaction work and reduction of the material susceptibility to compaction (fig. 3). The obtained values of the coefficient $k_c$ ranged from 6.04 to 25.64 (J·g$^{-1}$)·((g··cm$^{-3}$))$^{-1}$. Wherein at the moisture content of 10% there was no statistically significant differences in the values of $k_c$ resulting from type of compacted material ( p> 0.01). However, further increase of moisture caused that the highest susceptibility to compaction was each time observed for the beet pulp without binders.

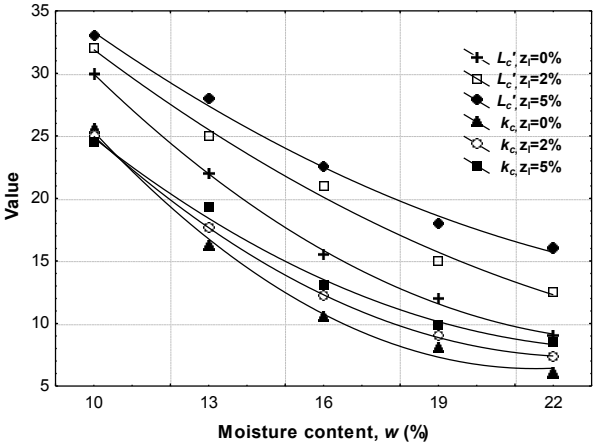


**Fig. 3.** Correlation between compaction effort ($L_c$'), coefficient of susceptibility to compaction ($k_c$) and moisture content ($w$) at various binder content levels ($z_l$)

## MECHANICAL STRENGTH OF THE AGGLOMERATE

The results of mechanical resistance $\sigma_n$ showed that, for each type of material, the agglomerate strength increased with an increase of moisture content in the range of 10 – 19% (Fig. 4). However, the increase of moisture content to 22%, for all raw materials, resulted in a decline of the parameter value. Mechanical strength ranged from 0.75 to 2.21 MPa. The highest values were observed for the agglomerates obtained during compaction of the pulp with 2% addition of calcium lignosulfonate, and at 19% moisture. Slightly lower values were noted for the agglomerate obtained from the pulp containing 5% molasses. It should also be noted that with the increase in moisture, the differences in the values of $\sigma_n$ (resulting from the impact of the type of test material) remained stable. Addition of binder to the pulp allowed to

achieve an average 34% increase of agglomerate strength $\sigma_n$ compared to the control material.

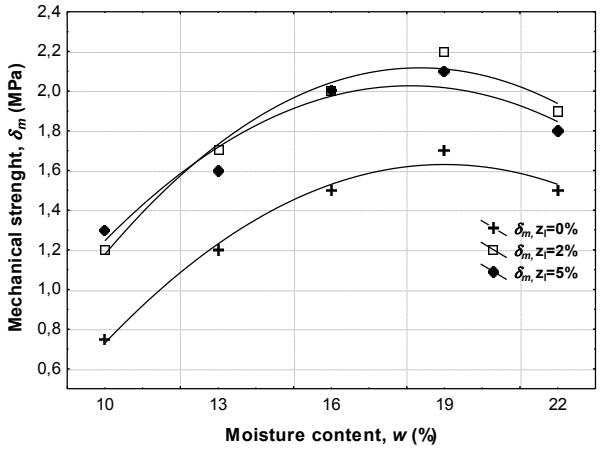


**Fig. 4.** Correlation between mechanical strength of agglomerate ($\delta_m$) and moisture content ($w$) at various binder content levels ($z_l$)

## CONCLUSIONS

The following conclusions can be drawn from the results of the study:

1. It was found that the density of the material in the compaction chamber – both for the pulp with and without binders – increases with increasing moisture content, about 16% on average. The increase of moisture in the range 10-16% results in an increase in density of the agglomerate (average of 28%). In the case of $r_a$ a significant role of binders addition was also confirmed and the resulting average rise of the density achieved 13.5%.
2. The density of agglomerate obtained from the pulp with binder addition was on average 4.2 times higher than the initial material density $\rho_n$. For the control sample, the parameter $S_{za}$ was on average 3.6 higher.
3. Specific work of compaction and material susceptibility to compaction decreased with increasing moisture content of the material. Mean changes were -61% and -70%, respectively.
4. It was shown that increasing moisture content from 10 to 19% favors higher mechanical strength of agglomerates (on average 83%). Addition of binders to the pulp increases the value of $\sigma_n$ on average by 34%.
5. In the case of density and mechanical strength of agglomerates, application of molasses in amount of 5% gives results comparable to the use of 2% calcium lignosulfonate additive. However, with regard to the specific work of compaction, better results were obtained for the pulp with addition of calcium lignosulfonate.

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## CIŚNIENIOWE ZAGĘSZCZANIE WYSŁODKÓW BURACZANYCH – PARAMETRY PROCESU I JAKOŚĆ AGLOMERATU

**Streszczenie:** Przedstawiono wyniki badań nad określeniem wpływu wilgotności (od 10 do 22%) i dodatku lepiszcza w postaci melasy (5%) i lignosulfonianu wapnia (2%) na parametry zagęszczania wysłodków buraczanych. Zagęszczanie przeprowadzano przy wykorzystaniu maszyny wytrzymałościowej Zwick typ Z020/TN2S i zespołu prasującego z matrycą zamkniętą. Zaobserwowano, że wraz ze wzrostem wilgotności rośnie gęstość materiału w komorze i gęstość aglomeratu (średnio o 28%). Wykazano, iż najniższa energochłonność zagęszczania odnosiła się do zagęszczania wysłodków bez dodatku lepiszcza (wartość średnia – 17,71 $J \cdot g^{-1}$). Najwyższa zaś dotyczyła wysłodków z 5% dodatkiem melasy (23,53 $J \cdot g^{-1}$). Stwierdzono, że najwyższą odpornością mechaniczna (2,2 MPa) charakteryzował się aglomerat wytworzony z wysłodków z dodatkiem 2% lignosulfonianu wapnia, zagęszczanych przy wilgotności 19%.
**Słowa kluczowe:** wysłodki buraczane, zagęszczanie, wilgotność, lepiszcza, lignosulfonian wapnia, LignoBond DD, melasa.

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# The Impact of Potato Sampling Site on Selected Texture Properties

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**Summary.** The paper presents the results of research on the impact of sampling site on the textural properties of potato tubers. Selected indicators of texture, i.e. hardness, fracturability, springiness, cohesiveness and chewiness were determined using double compression test TPA. The study was conducted on samples from well defined layers (upper layer, middle layer, lower layer) and zones (A, B, C), because their structure is heterogeneous. The samples were compressed in the vertical and horizontal direction. The results were statistically analyzed using Statistica 6.0. The research has shown that the sampling location has a significant impact on the value of all the parameters of potato texture. At the vertical compression of the material, the hardness decrease also caused a decline in the other studied parameters, while at the horizontal compression, in general, the increase in hardness caused the increase in fragility, cohesiveness and chewiness, while the springiness decreased.
**Key words:** potato, textural properties, sampling site.

## INTRODUCTION

Growing consumer interest in healthy food has forced the producers to improve production conditions and selection of such varieties of potatoes that meet the requirements, depending on the destination [9, 7]. The use of potatoes is very wide, from human consumption by feed through to manufacturing. In each of these applications the potatoes are used with selected properties associated with their chemical composition [2, 5]. The chemical composition of tubers varies depending on the variety, environmental conditions and, in particular, weather conditions. In a potato tuber there is about 75% water and 25% dry mass. The energy value of potatoes is not large and is 87 kcal·100 $g^{-1}$ (366 kJ·100 $g^{-1}$) [4, 17].

In recent years, we have seen changes in the use of potatoes. The use of the plants for industrial purposes, such as starch or alcohol, has been reduced (from about 3 million tonnes in 1989 to about 1 million tons in recent years). The use of potatoes in fattening animals has been steadily decreasing. Only the consumption of potatoes has remained almost constant. However, there has been an increase in processing vegetables for food [11, 12, 14].

The most important task of fruit and vegetable industry is the preservation of harvest, which allows consumption of products throughout the year. Management of fruit and vegetables on a commercial scale is a very difficult organizational sector of the food industry. Storage of potatoes requires such conditions that will reduce losses and the loss of mass of tubers and shall encourage the maintenance of selected quality characteristics required for specific directions for use. There are four stages of storing potatoes:

Stage 1 – this is the initial period of storage, which consists of drying and healing combined with cork peel. The length of this period should not last more than 2 weeks at 15ºC.

Step 2 – consists in cooling the potato tubers. Within a day, the lowering of temperature in the range of 0.2-0.5°C with humidity of 90% to 95%. This period may last from 4 to 8 weeks from the start of cooling.

Step 3 – a long-term storage. At this stage the destination of the stored potatoes plays an important role . Potatoes should be stored at 5-7ºC and seed at 3-5ºC.

Step 4 – consists in a slow raising of the temperature to 12-15ºC for 2-3 weeks in order to prepare for the use of potatoes [3, 16, 18].

Texture of the pulp is the basis to qualify for a particular type of potato utility and consumption [13]. It is a fast and objective evaluation that does not require a large amount of time and work, and allows you to get accurate results. Texture shapes our preferences and is an indicator of freshness [15]. It plays an important role in the transport and processing, as it determines the handling of the product. The application provides a comprehensive summary of product characteristics, taking into account the mechanical properties and geometry [1, 8]. The size, shape (Fig. 1), morphology and anatomy of potato (Fig. 2) have an impact on the formation of defects, both internal and external. [6]

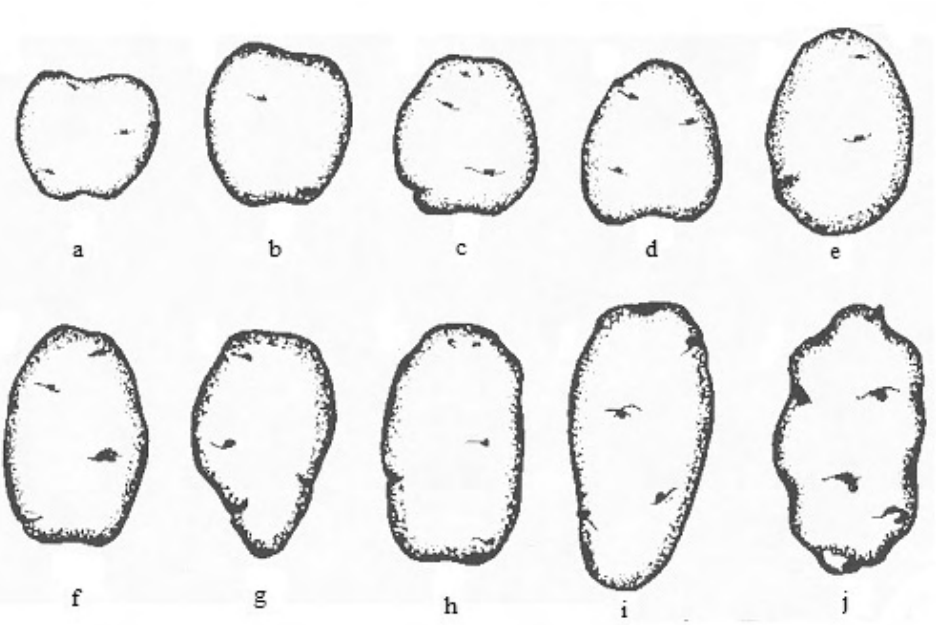


**Fig. 1.** Shapes of potato tubers, a – transversely oval, b – round, c, d – round-oval, e, f – oval, g, h – oblong-oval, i – elongated, j – irregular

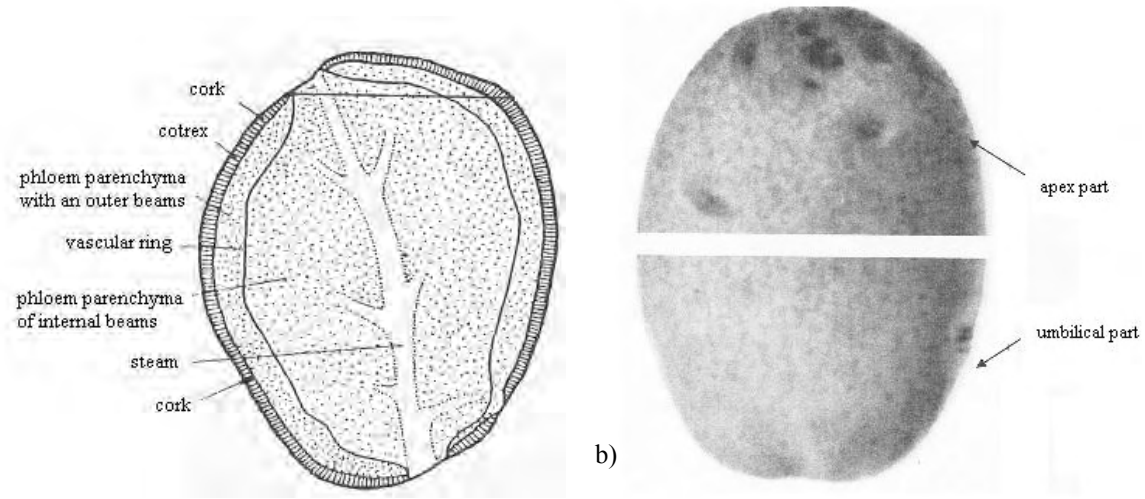


**Fig. 2.** Construction of a potato tuber: a) anatomical (longitudinal), b) morphological

For materials with a heterogeneous textural structure, the texture is a critical distinction for its evaluation and attributes considerable importance. Therefore, it is important to constantly test the quality of tubers [10].

## OBJECTIVE AND SCOPE OF RESEARCH

The aim of this study was to investigate the effect of sampling site on the textural properties of a potato.

The scope of the study included the initial preparation of raw materials, cutting out samples of potato tubers, testing the strength of the material and their statistical description.

## METHODS

The investigation included potatoes of a new variety – Madeleine. The variety is early, they have a light yellow skin and yellow flesh. The tubers are oval-oblong, they have shallow eyes and a uniform shape. They are intended for edible seed – consumer needs, suitable for French fries, chips and starch production.

The vegetables came from private field crops in the province of Lublin. The potatoes were grown on the third grade soil. Fertilization, beauty and safety measures were carried out using mechanical equipment. Harvesting was done manually in the phase of technological maturity. Acceptable vegetables were selected in terms of shape and size, items with visible signs of damage or disease were discarded. Tubers of similar, uniform shape were selected. The shape of the potatoes was similar to the round one.

Material for the study was collected from the 10th week after harvest for a period of 7 days. Vegetables were stored in a vault at the temperature not exceeding 6°C and relative humidity of 95%.

In each tuber first a slice was punched with thickness of 20 mm from the central portion toward the longitudi-

nal direction. Then the cuboid was excised of dimensions 60x60x20 mm, which was first divided into three layers (upper, middle and lower) with the thickness of 20 mm, and then the three zones A, B and C (also the thickness of 20 mm). This resulted in cubes with 20 mm sides. The site of sample cutting is shown schematically in Fig. 3. To determine the effect of the change in mechanical properties, samples were excised from twenty potatoes. In order to be able to carry out mathematical statistical analysis, the position of the individual samples was determined. Coordinate system *x*-*y* assumed the intersection at the point 0. The *y*-axis coincides with the vertical axis of zone B, and the *x* axis with the horizontal axis of the central layer. Vertical axes in the zone A and B were spaced from the axis *y*, respectively -20 and +20 mm, and the horizontal axis of the top layer samples were also spaced about -20 and +20 mm from the axis *x*.

The tests were subjected to double compression on the texture-meter TA.XT at the speed of the head 50 mm·min$^{-1}$. The compression was carried out at constant 50% deformation of the sample height, and the time interval between sets was 5s. Afterwards ten samples from all were compressed in the vertical direction (*y*), and ten in the horizontal direction (*x*). Each series of tests was carried out in triplicate.

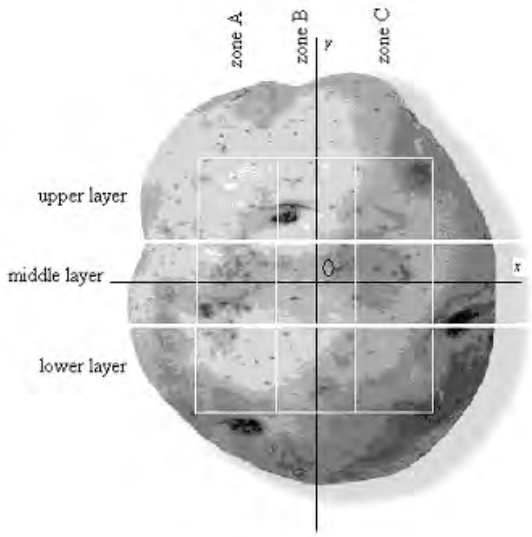


**Fig. 3.** Schematic of sample cutting

The analysis of the measurements in the form of texturographs of the coordinate system of two force-deformation allows a determination of the following textural parameters: hardness, fracturability, cohesiveness, springiness and chewiness:

– hardness, i.e. the maximum force during the first cycle of compression;
– fracturability, force assigned to the first significant peak in the curve of the first compression;
– springiness, that characterises the degree of recovery of the initial form;
– cohesiveness characterising the forces of internal bonds that hold the product in one piece;
– chewiness which is a measure of force required to chew a bite of food to make it ready for swallowing; it is defined as the product of hardness, cohesiveness and elasticity.

## RESULTS

The average density of the raw material of the test was 1121 kg·m$^{-3}$, and the humidity 81.3%.

Figure 4-8 shows the values of taps in the texture of the potato depending on the place of sampling and the compression direction.

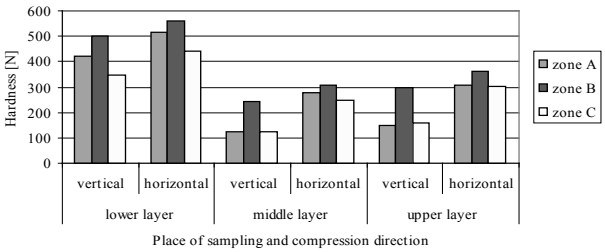


**Fig. 4.** The dependence of the hardness of the layer of potato and the sampling zone on the compression of raw materials vertically and horizontally

One of the parameters, which are determined by the strength tests was the hardness of potato (Fig. 4). The highest hardness of the samples was characterized by the lower layer of the tuber in the zone B when the value of the horizontal compression was 558.026 N characteristics, and with a vertical compression 502.184 N. In each case, the highest hardness of the material was found in zone B, which is the site of the core tubers.

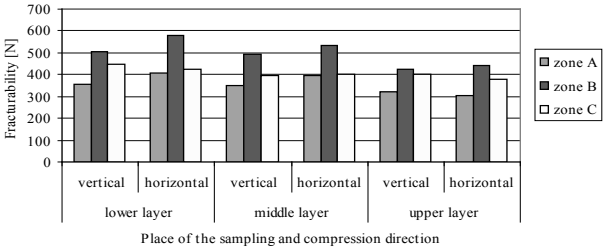


**Fig. 5.** Dependency of fracturability on the layer of potato and the sampling zone at the compression of raw materials vertically and horizontally

Fracturability of potato was different, depending on the location from which the test material came. The highest fracturability occured in the raw material downloaded from the bottom layer in zone B, at the horizontal compression the determinant value amounted to 582.268 N. As we got closer to the apical part, the fracturability of potato decreased: the middle layer was 530.956 and 443.488 N for the top layer. It was observed that the vertical compression fragility of the material from the core was also the largest at the top of potato and decreased as it approached the umbilical portion. The value of the determinant was in the range of 502.120 to 423.273 N.

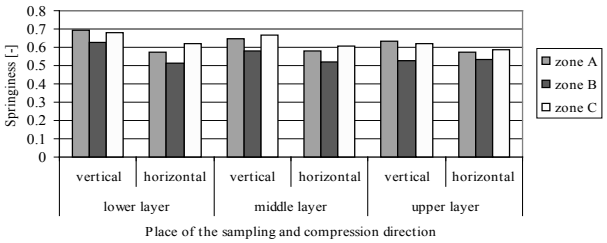


**Fig. 6.** Dependency of elasticity of the layer of potato and the sampling zone at the compression of raw materials vertically and horizontally

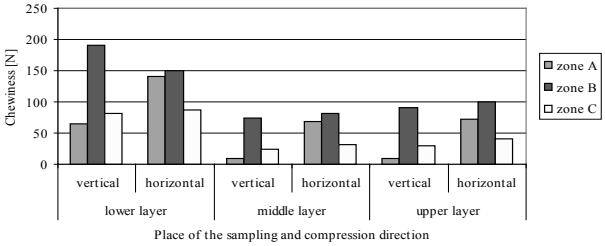


**Fig. 8.** Dependence of chewiness on the potato layer and sampling zone for the compression of raw materials vertically and horizontally

Another feature being determined during strength testing was springiness of the material. The potato was the least resilient in zone B, the lowest value of this feature was observed in the bottom layer with a horizontal compression, where it was 0.512. The highest springiness of the crumb samples of the tubers occurred at the lower layer of vertical compression. The values of indicators for zones A and C were respectively 0.692 and 0.683.

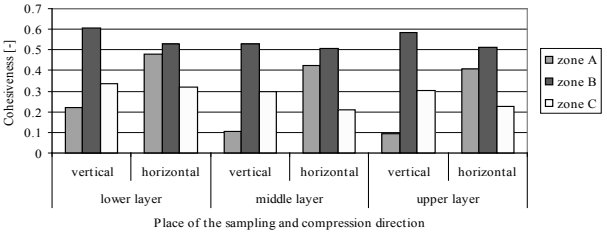


**Fig. 7.** Dependence of potato cohesiveness of the layer and the sampling zone at the compression of raw materials vertically and horizontally

It was observed that the cohesiveness of potato was the highest for samples from the core layers of all tubers at each direction of compression.

The highest level of chewiness was reached during the tests on the lower layer B in tubers, at vertical compression of the samples (190.645 N), and on the lowest zone in the middle layer A, the value of which was as much as 61% lower. In all cases, the smallest crumb chewiness occurred in tubers from zone A. For the bottom layer, the determinant value was 64.385 N, for the middle layer 8,539 N and for samples from the umbilical portion of the potato 8,970 N.

Based on the results it can be concluded that the material hardness decreases at vertical compression, which also causes a decline in the other studied parameters. In contrast, generally, the horizontal compression increases hardness and also causes an increase in the fracturability, cohesivenes and chewiness, while the springiness decreased.

Research on the fragility of the tubers showed that the most fragile was the material downloaded from zone B (samples compressed vertically and horizontally), that is from the core of the potato.

## CONCLUSIONS

1. Sampling site has a significant effect on the value of all the parameters of potato texture.
2. During the tests, at the compression of potato vertically and horizontally it can be seen that the texture parameters of determinants, i.e. hardness, fracturability, cohesiveness, chewiness were by far the highest for the material in zone B (the position where the core of tubers is).
3. The hardness and fragility of potato was the highest in the core of tubers and in each case the determinant of texture assumed higher values at vertical compression than horizontal one.
4. For each of the layers springiness received at the lowest zone B was higher for vertical than horizontal compression.

**Table 1.** Regression equations and coefficients of determination $R^2$ describing the variability of individual determinants of potato texture shared into zones and layers as: vertical and horizontal. The equations are valid for values of $x$ and $y$ ranging from -20 to +20 mm and were determined at the level of statistical significance $\alpha \leq 0.05$

| Determinants of texture | Compression process | Regression equations | Coefficients of determination $R^2$ |
|---|---|---|---|
| Hardness [N] | vertical | $H = 248{,}441 - 5{,}597y - 0{,}316x^2 + 0{,}372y^2$ | 0,968 |
| | horizontal | $H = 277{,}564 - 4{,}501y + 0{,}34\ y^2$ | 0,843 |
| Fractubility [N] | vertical | $Fr = 480{,}030 + 2{,}205x - 1{,}805y - 0{,}259x^2$ | 0,897 |
| | horizontal | $Fr = 512{,}166 - 0{,}298x^2$ | 0,535 |
| Springiness [-] | vertical | $Spr = 0{,}577 - 0{,}0018y - 0{,}0002x^2$ | 0,949 |
| | horizontal | $Spr = 0{,}524 + 0{,}00077x + 0{,}00017x^2$ | 0,912 |
| Cohesiveness [-] | vertical | $Coh = 0{,}573 + 0{,}004x - 0{,}00087x^2$ | 0,938 |
| | horizontal | $Coh = 0{,}517 - 0{,}0047x - 0{,}00043x^2$ | 0,888 |
| Chewiness [N] | vertical | $Ch = 90{,}910 + 0{,}442x - 1{,}715y - 0{,}207x^2 + 0{,}104y^2$ | 0,898 |
| | horizontal | $Ch = 85{,}396 - 1{,}395y - 1{,}032x + 0{,}096y^2 - 0{,}093x^2$ | 0,894 |

5. Chewiness and cohesiveness had the highest value in the core material. Higher values of cohesiveness were observed in the case of vertical compression than for horizontal one, for chewiness the values were variable.

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## WPŁYW MIEJSCA POBRANIA PRÓBEK NA WYBRANE WYZNACZNIKI TEKSTURY ZIEMNIAKA

**Streszczenie.** W pracy przedstawiono wyniki badań wpływu miejsca pobrania próbki na właściwości teksturalne bulwy ziemniaka. Wybrane wskaźniki tekstury, tj. twardość, kruchość, sprężystość, kohezyjność oraz żujność określono za pomocą testu podwójnego ściskania TPA. Badania przeprowadzono na próbkach pobranych ze ściśle określonych warstw (warstwa górna, warstwa środkowa, dolna) i stref (A, B, C), ponieważ jego struktura jest niejednorodna. Próbki były ściskane w kierunku pionowym i poziomym. Uzyskane wyniki opracowano statystycznie korzystając z programu Statistica 6.0. Z badań wynika, że miejsce pobrania próby ma istotny wpływ na wartość wszystkich parametrów tekstury ziemniaka. Dla materiału ściskanego pionowo spadek twardości powoduje również spadek pozostałych badanych parametrów, natomiast dla surowca ściskanego poziomo wzrost twardości powoduje wzrost kruchości, kohezyjności oraz żujności i spadek sprężystości.

**Słowa kluczowe:** ziemniak, właściwości teksturalne, miejsce pobrania próbki.

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# Analysis of the Use of Logistic Systems in Motor Transport Facilities Based on the Example of a Car Showroom

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**Summary.** This paper describes the role of logistic system in the effective operation of motor transport facilities. The description covers systems that influence the improvement of the organization of work in such facilities based on the example of a selected car showroom and improvements related to product supply and distribution (e.g. new and used cars or indispensable spare parts for repair work). The paper also presents the effect of marketing and control activities on the improvement of the offered services as well as on the acquisition of new customers.

**Key words:** logistic systems, motor transport facilities, car showrooms, car dealerships.

## INTRODUCTION

Motor transport facilities, such as filling stations, repair shops or diagnostic centres are important for proper and safe operation of the motor vehicles used by individuals and transport companies which carry out various kinds of tasks related to relocation of people or cargos [1, 5]. For the provision of services in the technical facilities to the highest standards, the equipment, the qualified staff and various kinds of systems to facilitate the work are of considerable importance.

The activities influencing the improvement of the operation of motor transport facilities include the use of appropriate logistic systems. They facilitate the organization of planning, control and inspection tasks. They enable proper management of supply, production, distribution and marketing, which also contributes to the improvement of the offered services. The currently used logistic systems are integrated with computer programs that enhance effectiveness of companies and help them develop and make profits.

## THE ROLE OF THE LOGISTIC SYSTEM IN MOTOR TRANSPORT FACILITIES

A logistic system is a set of closely connected elements, the aim of which is to facilitate the management in different enterprises, including motor transport facilities. A logistic system is characterized by cohesion and flexibility. The cohesion consists in that all systems are dependent on each other, and any change in one of the systems creates pressure for changes in the other systems. Whereas the flexibility consists in that a change in the external factors, i.e. the market demand, competition or, e.g., new regulations, does not involve any changes in that particular system but it accommodates itself to the new conditions. Criteria of identity for logistic systems are presented in Table 1 [7, 13, 15].

Proper organization of work is of vital significance in motor transport facilities. The responsibility for the proper organization of work lies with the company's management board. Its aim is to establish and authorize projects the company needs for its efficient operation. The managers' basic objectives include establishing the shared vision, mission, strategies and goals of the company. In order for the management to be able to achieve the intended objectives, they must have access to all information on the parameters that shape the particular organizations structures of the company, the results it achieves as well as on the costs that have an adverse effect on its development. The cost-effectiveness analysis, which consists in calculation of the business-related costs, and the gain-loss evaluation are of great importance to every company.

In motor transport facilities, it is important to properly plan all the assignments to be undertaken and to ensure equipment required for their execution. In order for the services to be offered at a high level, the qualifications of

**Table 1.** Criteria of identity for logistic systems

| No. | Criteria | Systems |
|---|---|---|
| 1. | Structural and organizational criterion | – Planning system for gathering and organizing information necessary to launch a company.<br>– Organization system to execute the activities planned in advance and to organize all means essential for the company to operate.<br>– Steering system to control the mechanisms behind the company's operation.<br>– Control system responsible for controlling anything that makes the subject of the company. |
| 2. | Functional criterion | – Supply system to protect, store and supply the means needed by a company to make a product, i.e. machinery, equipment, materials, raw materials, components etc.<br>– Production system to make and manage the means supplied by the supply system.<br>– Distribution system to go between the production and the output market and to supply the product straight from the production line or warehouses to the customer, in the agreed quantity and within the specified time limit.<br>– Marketing system to promote the product and improve the production-customer relationship in order for the company to gain as high income as possible.<br>– Recycling system to recycle and utilize wastes, by which it can contribute to reduction of the environmental pollution. |

those employed in the particular technical facilities are also of vital significance [3, 20]. Internal and external controls are of considerable importance, too. They allow for detection and elimination of any irregularities. In addition, the controls support the planning and help coordinate the decision-making process.

Among the important systems in motor transport facilities there is also one that is related to the procurement as it ensures continuity of work. Appropriate reserves of raw materials or spare parts in the warehouses protect companies against costly stoppages. Each stoppage means that a service may be not completed in the specified time limit and, as a consequence, the dissatisfied customer and some profit are lost. The customer's satisfaction is the proof of quality of the offered services. The main demands and expectations of customers include easy access to all information, prompt completion of services, reliability and completion of orders in the manner expected by the customer. The equipment, instrumentation, meeting the requirements related to occupational health and safety as well as comfort and the aesthetic qualities of the service space also have an effect on the positive quality assessment of the offered services. The factors affecting quality of the offered services are named in Fig. 1.

Among major logistic systems, the distribution and the marketing ones are those that play an important role. The distribution system acts as a 'go-between' between the production and the output market. It deals not only with supplying a product or a service in the agreed quantity straight to the customer and within the specified time limit but it also completes all related formalities. The marketing system deals, in turn, with promotion of the product or service and with the improvement of the relationships with potential customers in order for the company make as high income as possible. The recycling system is another one that is important from the environmental point of view. This system is responsible for the recycling and utilization of wastes [17].

The following factors are to be taken into account in order to create a logistic system to manage a given motor transport facility [2, 14, 19]:
– Material factors: Adjustment of the service type to the rooms, means and conditions for relocation.
– Personal factors: Qualifications and organizational skills of the staff.
– Information factors: Storage, processing and data handling methods as well as the software level.
– Financial factors: Availability of all financial means.


**Fig. 1.** Factors underpinning the service quality in motor transport facilities

The proper operation of motor transport facilities is determined, apart from the logistic systems, by other factors which are presented in Fig. 2. Their efficiency may be enhanced by, inter alia, automation, mechanization and modernization, as well as by integration of the partial systems, suppliers, logistic units and customers.

## PLANNING AND WORK ORGANIZATION SYSTEM IN CAR DEALERSHIPS

The planning of work in car dealerships is one of the basic factors that have a direct impact on the company's development. The plans may be involve both short and long execution times. Most often, they are fixed by the company's management board and concern the company's overall activity [10]. Long-term plans may involve a wider range of services on offer, an increase in the company's productivity or its wider influence on the market. These plans may not be executed without prior implementation of short-term plans. In order to accomplish each planned activity, the company should analyse the data and make use of the staff's engagement, their competences, skills and qualifications. Implementation of an appropriate employee motivation system is very helpful here. This may involve urging the employees to carry out specific tasks and taking into account, at the same time, their ambition needs, i.e. the needs for fulfilment or success etc.,

Car showrooms offer a wide range of services. Apart from their basic function which is the sale of new and used vehicles, they also repair, rent out or insure vehicles. The proper execution of the particular tasks is the responsibility of the highly qualified staff in different departments. In order for the particular departments making up the organizational structure of the dealership to be improved and their efficiency enhanced, appropriate systems and computer programs to streamline all activities must be introduced (Fig. 3) [6,11]. Such programs are usually based on simple solutions consisting in that that important information is put in an integrated customer data base that can be accessed by the managers of the sales departments for new and used cars, repair and marketing. Additionally, these programs make it possible to establish work schedules, account for the working time and to keep a task accomplishment register. In the case of a repair shop, appropriate programs give the opportunity to quickly and more precisely estimate the repair time and costs and to plan the work for the individual stands for all vehicle brands handled by the shop in a more efficient way.

In a car showroom selected for the analysis, the sales staff have workstations equipped with computers with access to the Internet and the Global Connect and eCARS21 programs (Table 2).

They also have commercial offers and all the documents necessary to order a car. In order for the sales assistants to be able to offer the highest service quality, they are trained

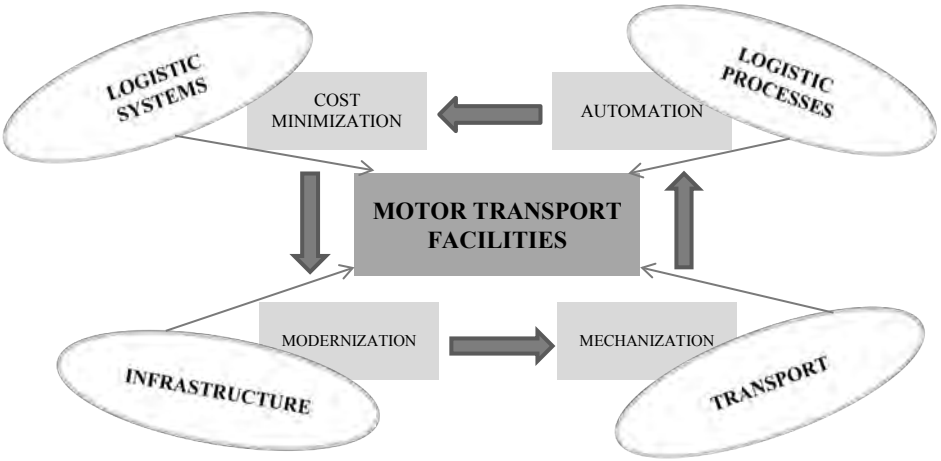


**Fig. 2.** Factors underpinning the effectiveness of motor transport facilities


**Fig. 3.** Function of the planning and organization system in car showrooms

**Table 2.** Characteristics of the Global Connect and eCARS21 programs

| Global Connect | eCARS21 |
|---|---|
| – Introduced in 2010.<br>– Originally, this was a program using the English language only but after some time, the Polish version was added.<br>– Uses Internet connection which enables searching information in a continuous and quick manner.<br>– Enables continuing upgrade including the changes made by the company which prevents entry of invalid data during making an order.<br>– Has a tool platform divided into orders, sales, repairs, spare parts and business service. | – Ensures easy service and independence as well as uniform communication with the manufacturers' systems, including Global Connect.<br>– Is intended for use by any dealership, irrespective of its size.<br>– As an application that supports work with many warehouses and many branches, the system is based on a technology that helps minimize the costs of operations between the branches.<br>– Has a range of modules, one of which being a module to support the sale of cars. |

in customer service, i.e. they acquire skills in the following areas:
- establishing contact and building up appropriate relationships with the customer,
- discerning the needs and the current situation of the customer,
- presentation of the company and its commercial offer,
- methods to manage the customer's problems,
- effective methods to conclude sale transactions.

## SUPPLY AND DISTRIBUTION SYSTEM IN CAR DEALERSHIPS

An important task of the supply and distribution system in the car showrooms is supply chain management – delivering vehicles from producers to clients in the required time limit, whilst ensuring transport security guarantees. Safe movement of vehicles is an extremely important element of distribution, so all showrooms should cooperate with reliable transport forms that perform their services at a high level and in a timely manner, have appropriately suitable transport available and a highly-qualified work team. A well-organized supply and distribution system should also be distinguished by maximizing services while at the same time minimizing costs [12,16].

Car dealerships can use a variety of computer programs to improve their supply and distribution systems. They facilitate demand forecasting and quality and supply management; distribution planning; warehouse inventory management; efficient data exchange with suppliers, customers and other systems; radio frequency identification technology services; and control of serial numbers, creating and service of contracts and repair orders, as well as cost-benefit analyses.

The supply and distribution in the analysed car dealership was streamlined by the Global Connect and eCARS21 systems. Global Connect has a procurement function that is divided into tabs related to cars, car composition and the prices for specific models. Support for the procurement function is done only by the sales manager. Each dealer that uses Global Connect is tasked with ordering approximately 20 cars from the factories each month. The cars are manufactured in the factories and then are moved to warehouses, where they await transport to the dealer. These cars can stay in the warehouse without a fee for up to 30 days in cases where a dealer has filed an order in the amount defined in the assignment. If the dealer has not fulfilled the monthly order requirements, then interest will be charged for the storage of the vehicles. The eCARS21 program includes, among other things, a sales module that streamlines tasks, i.e. appraisals, discount policies, orders, taking inventory and commissions. This module supports the sales of new and used cars, including internal margins, accounting for old cars and descriptions of cars available in the warehouse. The module's interface is straightforward and intuitive, leading to improved performance of the sales department. The model has built-in tools for sales management. These tools work in an on-line mode, which helps with rapid sales and customer information management, inventory control as well as in the preparation of cost estimates. Additionally, the tools manage catalogues of new and used cars, as well as orders for new cars.

Distribution in the described car dealership is done in two ways. One is the execution of a "tailored" order, that is, to meet the client's specific needs, while the second is related to the ordering of vehicles by the dealer to the dealership. In case of ordering cars to meet the clients' needs, production of the car is faster than those ordered for the warehouse. When ordering, the dealer has the opportunity to define the week of production, i.e. designate a date when the car will be manufactured. Another option is for the dealer to order cars with different specifications without customer input for the warehouse. These cars are ready for sale on the spot, but there is no option for individual customization. This involves risk, as some of the options chosen by the dealer may not appeal to customers. Thus, this car could remain at the dealership and, after a certain time, accrue losses.

## MARKETING SYSTEM IN CAR DEALERSHIPS

In car dealerships, a significant role is played by the marketing department, which deals with the exchange of information between the company and customers, contractors, suppliers and the market in order to obtain financial advantages. The staff of the marketing department systematically collects and analyses information related to the current needs of clients, such as checking which car models have the highest demand, which can be afforded by the average consumer, what accessories are the best options, what the relationships are between the class of the car and its price, and what is offered by competitors. This and other information is necessary in developing the company's

operational strategy with the aim of attracting the most customers and eventually achieving the greatest profits with the lowest possible costs. The marketing department is also responsible for supporting the decision-making process in the showroom (Fig. 2.4).

So that an excess of information and leading many advertising campaigns does not limit the reaction time of the marketing team to significant changes on the market, they can make use of the following programs [4, 8, 18]:

– Analysis and reporting the results of all marketing activities.
– Control the management of funds meant for advertising.
– Dividing customers into different groups and automated marketing.
– Comparing actual and projected revenues.
– Price management and discounts for goods and services.
– Simulations associated with the creation of tenders and contracts.

In the assessed car showroom, one way of attracting customers is a number of promotional actions. One of these actions is a large New Year's sale, which has an offer consisting of discounts for cars produced in the past year. The company also offers discounts for "professional groups", including pharmacists, auditors, journalists and academics.

## CONTROL SYSTEM IN CAR DEALERSHIPS

In dealerships, the control system plays an important role because it is responsible for proper execution of all assigned tasks by all departments active in the company. Controls, both internal and external, have the objective to detect any irregularities and deviations from the established rules and plans. In order for the control system to be effective, it must be properly prepared and adapted to the conditions prevailing in a particular company. Choosing a control system depends on the company's size – the number of employees, branches, the scope and area of its operations (i.e. geographical factors), as well as on the types of cars, spare parts and any related services being offered.

Checks in dealerships can be on the department for sales of new and used cars, services performed in the repair shop and marketing actions aimed at encouraging customers to take advantage of the company's offers and in pursuit of operational benefits. Inspections may also be related to monitoring the implementation level of an established concept by the firm as well as controlling all processes taking place in real time and the results achieved after a certain period of activity. The control system usually contributes to increasing employee productivity in the dealerships, improving the quality of the services offered and also achieving the results intended by the firm [9].

A very important factor that should be monitored by the employer is working time. The point here mainly is about the time employees spend at work and on activities connected to it, as well as on what their unproductive habits are. Programs allowing employers to increase employees' self-discipline and eliminate undesirable behaviours are increasingly used in car dealerships. The programs automatically collect data on the activities performed by employees, registering only specific events and the duration of use of individual programs without interfering in the privacy of the employees. Cameras monitoring all areas of the company have also had an important impact on safety in car dealerships. They ensure the protection of dealership property, in the repair shop and the warehouses, from theft and all forms of vandalism as well as making an impact on improving employees' performance.

An important aspect in the functioning of the firm that also is subject to checks is the protection of the natural environment. Increasingly, car dealerships create conditions conducive to building awareness for protecting the environment, the rational use of energy and natural resources, and respecting environmental requirements. They promote 'ecological car driving' – turning the engine off when shutdowns last more than one minute, earlier changes to high gears, ensuring a smooth ride without unnecessary acceleration and breaking, avoiding opening windows to decrease resistance movement and using air conditioning only when necessary. All of these activities are beneficial for drivers, as they help minimize fuel consumption, which contributes to minimizing significant savings in vehicle operations as well as decreases $CO_2$ emissions – all of which contribute to protecting the environment [17].

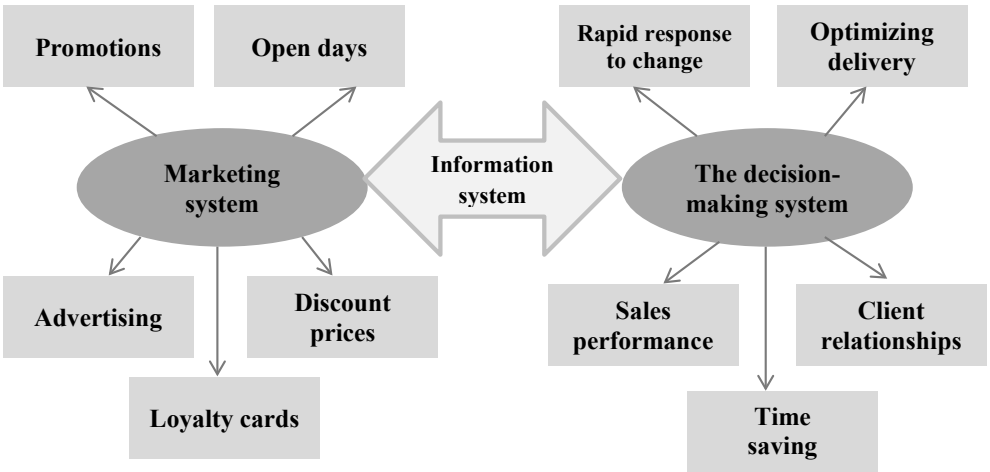


**Fig. 4.** Diagram of the relationship between the operation of the marketing and decision-making systems

## CONCLUSIONS

Like in any development-oriented company, the use of logistic systems in car showrooms is extremely important, because it contributes to the improvement of the efficiency of their operation. The improvement of the executed tasks through implementation of relevant programs helps save time which can be used in other areas of the company's activity, for example to raise the service standards, thus acquiring customers.

Among the many systems that have a positive impact on the function of showrooms, those related to organization of work and to control of all the company's objectives deserve special attention. Good organization of work, with relevant equipment and programs used for this purpose, has an impact on the improvement of all the activities of the staff, and in particular, on the completion of all orders in the proper and timely manner, which is particularly essential for the customers making use of services of the specific showroom. Customers satisfied with the offered services will come back and encourage the others to come, which will allow the company to gain financial advantages it needs for further operation.

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## ANALIZA ZASTOSOWANIA SYSTEMÓW LOGISTYCZNYCH W PRZEDSIĘBIORSTWACH TRANSPORTOWYCH SA NA PRZYKŁADZIE SALONU SAMOCHODOWEGO

**Streszczenie.** Przedstawiono rolę systemu logistycznego w efektywnym zarządzaniu przedsiębiorstwem transportowym. Opisane są systemy, które pozytywnie wpływają na organizację pracy w takich przedsiębiorstwach na przykładzie wybranego salonu samochodowego oraz ulepszenia w zakresie dostawy i dystrybucji produktów (np. nowych i używanych samochodów oraz części zapasowych niezbędnych w celu dokonywania napraw). Artykuł przedstawia też wpływ marketingu i czynności kontrolnych na poprawę jakości oferowanych usług oraz pozyskiwanie nowych klientów.

**słowa kluczowe:** system logistyczny, przedsiębiorstwa transportowe, salony samochodowe, handel samochodami.

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# An Analysis of Selected Container Structures with Built-In Multi-Layer Composite Sheets with the Use of FEM

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**Summary.** In this paper presents 3D digital models of selected variants of container structures. A rigidity analysis of objects with built-in multi-layer composite sheets has been carried out and it has been compared with calculation results for classical structures. Numerical calculations have been performed with the use the Finite Element Method. The results obtained may be widely used in container structures designed for farming, building engineering and transportation.
**Key words:** computer aided design, finite element method, multi-layer composite sheets, polyoptymalization.

## INTRODUCTION

Large-size multi-layer composite sheets are made using the technology of in vacuum presses. Composite elements are used, among others, for building self-bearing mixed-use container structures. Composite elements of walls are used, among others, in farming for building freezers and utility rooms.

Composite sheets are glued in vacuum presses. The working principle of the press is based on the effect of negative pressure (vacuum) generated between a properly formed surface of the work table and a rubber membrane covering the elements of sheets to be attached with adhesive. The pressure force of the elements of a multi-layer sheet depends on the value of generated vacuum. The effect of negative pressure is obtained using a correctly selected vacuum pump which sucks off the air from the space between the work table and the rubber membrane [8].

Classical container structures are made using the technology of welding steel sections which form a framework the walls of which are made of metal sheets, and insulating materials do not increase the rigidity of the entire structure. A modification of a classical construction of containers involves attaching multi-layer composite sheets into a framework using adhesive. On the one hand they form external panels, on the other hand they increase the rigidity of the framework as well as improve its endurance parameters.

A multi-layer composite sheet consists of three layers:
– external layer – a 1-millimeter steel sheet,
– internal layer – a 50-millimeter composite material,
– there is an additional face layer made of plastic.

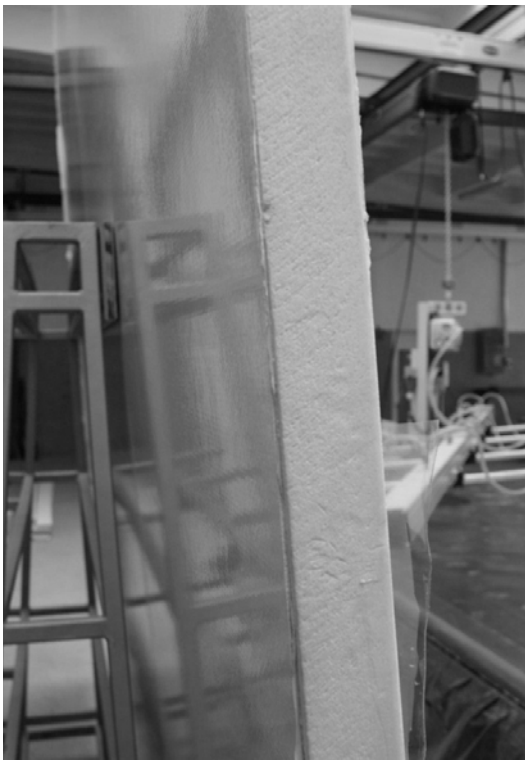

**Fig. 1.** Composite sheet

This paper presents issues related to digital modeling and endurance calculations of a framework of a classical container as well as its modification with composite sheets attached with adhesive.

In the next stages of this work endurance and rigidity calculations of selected variants of the container's structures using CAD systems (the Finite Element Method) were carried out. This resulted in building a container framework with composite sheets attached with adhesive as well as verification of numerical calculations at a testing station [2, 3, 4, 5, 12, 13].

## DIGITAL MODELS OF A FRAMED CONTAINER STRUCTURE AND ITS VERSION WITH COMPOSITE SHEETS ATTACHED WITH ADHESIVE

Digital models of different variants of the structure were performed using Inventor v13 system made by Autodesk. During the designing process, all geometrical, material and dynamic features both in their quantitative and qualitative forms were attributed to the said structures [18, 19, 20]. This allowed us to conduct simulation calculations using FEM. The FEM module is included in Inventor software and allows the user to perform numerical calculations directly on the object being modeled [7, 9, 10, 15, 16]. In Figure 2 solid models of selected variants of container structures are presented (framed and with composite sheets).

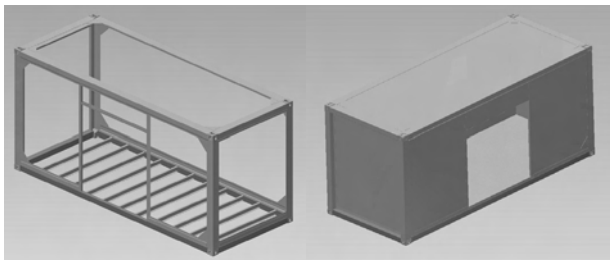

**Fig. 2.** Digital models of selected variants of container structures

## RIGIDITY CALCULATIONS OF CONTAINER STRUCTUERES

A digital displacement map of container models exposed to both their own and external load has been determined using FEM (the Finite Element Method) [14, 17, 21, 22]. An important stage of the work was to create an interaction model of a set of components, yet taking into consideration contact stress between two deformable objects. This task was performed by means of modeling the contact area using the "surface-to-surface" method as follows [21]:

- creating a geometrical model of an object,
- selecting properties of materials,
- determining the contact area,
- defining the type of contact,
- creating a network of finite elements,
- introducing boundary conditions,
- carrying out calculations,
- analyzing the calculation results.

The following construction materials were used in digital models of container structures. The framework of the container was made of steel sections, multi-layer sheets were made in the technology of gluing and consist of an external layer of steel sheets and an internal layer of composite Styrofoam.

Four load variants were taken into consideration while conducting calculations, which complies with the research method applied at certification laboratories. Forces in particular variants (except the dead load) were applied at upper corners of the container. The table below presents values of the applied forces:

**Table 1.** Values of forces applied

| Load case | Value of force |
|---|---|
| Vertical force | 318 000N |
| Transverse force | 75 000N |
| Longitudinal force | 75 000N |
| Dead load | ------ |

Fig. 3. presents three models of load cases of container structures. The method and location of forces applied complies with the actual research procedure used at measurement stations.

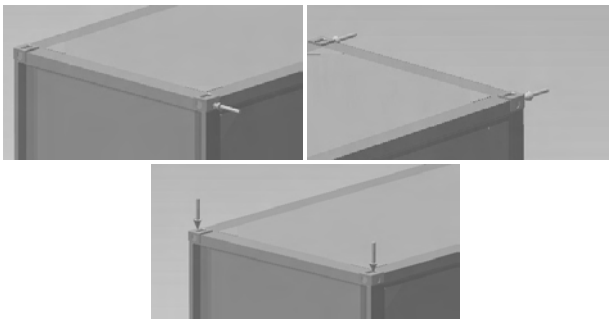

**Fig. 3.** Methods of applying forces at the measurement station.

In order to perform a FEM analysis degrees of freedom in the digital model of the container were eliminated using braces. Four "permanent" braces were used (elimination of six degrees of freedom); they were attached to lower surfaces at the basis of corner columns, according to the below presented figure.

**Fig. 4.** Stability brace in a digital model of the container

In a digital model of a container with composite sheets 782 contact pairs were generated between the framework and sheets.

While performing an analysis of this set (the container with composite sheets) models of 46 elements, being thin solids, were simplified. This allowed us to carry out calculations for a case in which a given structure includes elements of considerably differentiated dimensions [10].

Then the area of analysis was discretized as a result of which a network of finite elements was generated.

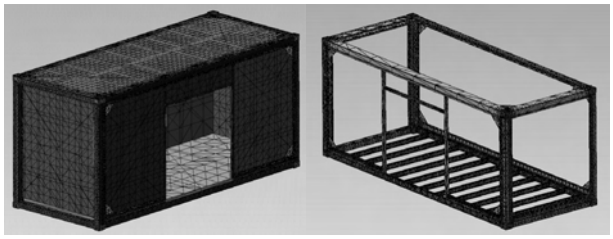

**Fig. 5.** Partitioning of container models into finite elements

With the use of the "solver" function of FEM digital displacement maps for particular container versions were generated. Fig. 6 presents displacements of the structure of the container without composite sheets exposed to vertical forces applied to upper corners of the framework.

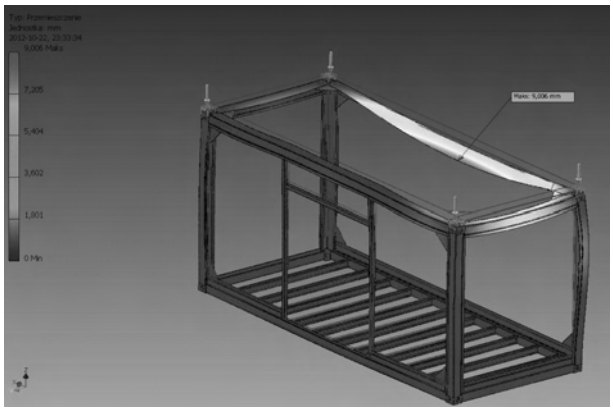

**Fig. 6.** Deformation map of a container without composite sheets

For comparison Fig. 7 presents a digital displacement map of a container with composite sheets attached with adhesive.

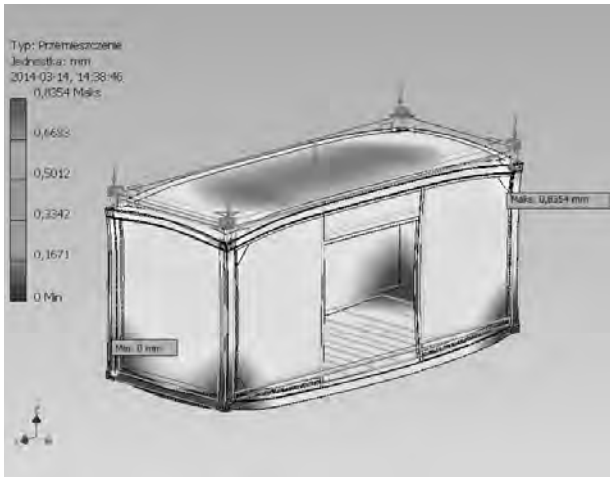


**Fig. 7.** Deformation map of a container with composite sheets

**Table 2.** Representation of obtained calculation results:

| Load type | Container without composite sheets | Container with composite sheets |
|---|---|---|
| Vertical force | 9,01 mm | 0,85 mm |
| Longitudinal force | 63,00 mm | 0,44 mm |
| Transverse force | 63,92 mm | 0,60 mm |
| Dead load | 5,58 mm | 0,08 mm |

The results of rigidity calculations indicate that the deformation of a container structure with composite sheets is more than tenfold smaller than in the case of a structure whose only bearing element is its framework. Multi-layer composite sheets used as container walls have an additional function and they increase to a considerable extent the rigidity of the structure under examination. The suggested solution proves to be effective in the case of high container storage, e.g. on cargo ferries or warehouses where the use of space is particularly important and containers are stacked up.

## VERIFICATION OF CALCULATION RESULTS OBTAINED

On the basis of the said digital model a prototype container was built by KONTENER Production of Building Elements LLC in Płock. Experimental studies at a research station involving the application of standardized values of forces to an actual structure were conducted. Empirical studies confirmed the results of numerical calculations [11]. The structure fulfilled the assumed criteria for rigidity and endurance. The deformation of the structure of the container with composite sheets did not exceed allowable values.

## CONCLUSIONS

The calculation results obtained were presented in the form of numerical maps and tabular representations. The analysis of theoretical calculations demonstrated compliance with the results obtained by means of empirical studies.

The use of CAD systems and FEM calculations in the case of problems discussed in this paper provide measurable advantages including:

– a considerable shortening of the time needed for studies owing to numerical analysis of numerous variants of container structures,
– conducting credible research using computer systems as early as at the designing stage,
– a possibility of designing container structures consisting only of multi-layer sheets after a prior numerical and experimental verification, without a steel framework, which will considerably reduce their costs and weight.

The research methodology suggested in this paper has been used in practice in order to perform contracts for the engineering industry, farming, civil engineering as well as defense industry.

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## ANALIZA Z ZASTOSOWANIEM MES WYBRANYCH KONSTRUKCJI KONTENEROWYCH Z WBUDOWANYMI WIELOWARSTWOWYMI PŁYTAMI KOMPOZYTOWYMI

**Streszczenie.** W pracy przedstawiono modele cyfrowe 3D wybranych wariantów konstrukcji kontenerów. Dokonano analizy sztywnościowej obiektów z wklejonymi wielowarstwowymi płytami kompozytowymi i porównano z wynikami obliczeń dla konstrukcji klasycznych. Obliczenia numeryczne zrealizowano z zastosowaniem metody elementów skończonych. Uzyskane wyniki obliczeń można wykorzystać w konstrukcji obiektów kontenerowych przeznaczonych dla rolnictwa, budownictwa oraz szeroko rozumianego transportu.

**Słowa kluczowe:** komputerowo wspomagane projektowanie, metoda elementów skończonych, wielowarstwowe płyty kompozytowe, polioptymalizacja.

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# Physical Phenomena Occuring in a Diesel injector Nozzle

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**Summary.** The article describes a physical phenomenon in a Diesel engine nozzle. Inside Diesel injectors there exists a fairly unknown micro-world. There are many factors like variable pressure and temperature, fluid mechanics phenomena and supersonic fuel flows. Injector nozzle is exposed to stress. There is combustion chamber with huge pressures and temperatures outside. Therefore, injector nozzle has to comply with strict requirements. The article describes pressures and temperatures found in an injector nozzle.

**Key words:** Diesel engine, fuel injector, injector nozzle, pressure and thermal phenomena

## INTRODUCTION

Diesel fuel injector works in a very variable micro-environment. Operating conditions are very hard because of high pressures and temperatures. There are many changeable phenomena inside it, like ballistics, erratic fluid flows, chemical and physical factors. All these phenomena influence the correct work of an injector [7, 13].

Injector's spare parts are made with maximum accuracy. The main objectives of Diesel injectors are spraying and distributing fuel in combustion chamber. To comply with all these terms, the determined conditions have to be kept. The article describes the two phenomena exerting the highest influence on pressure and temperature in Diesel injector,.

## AIM AND SCOPE OF THEORETICAL RESEARCH

Aim of researches is pressure and thermal injector nozzle analysis during work at maximum load [2]. Indicated pressure is 160 MPa. Theoretical analysis provides pressure and temperature changes on nozzle surface. Theoretical researches have been made in Solid Works application. Picture 1 shows the researched injector nozzle.

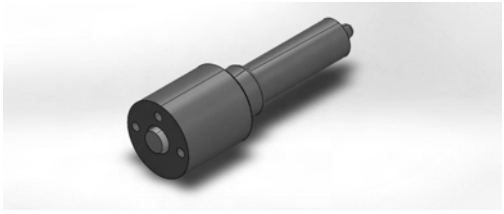

**Fig. 1.** Researched injector nozzle

## PRESURE PHENOMENA OCCURING IN INJECTOR NOZZLE

Tension experiment was made by using finite – element method with Solid Works program. Research was made on the influence of pressure inside injector coming from fuel on nozzle surface [6]. On the basis of real value of fuel pressure the experiment was carried out on tension inside injector nozzle. An element was put on solid net based on curvature [4, 5].

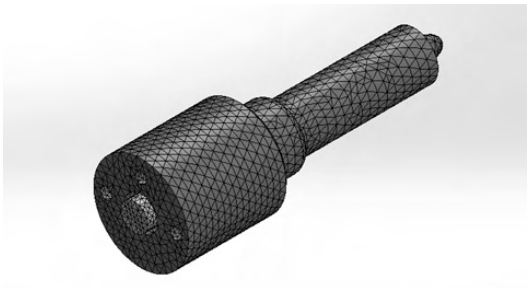

**Fig. 2.** Solid net on injector nozzle

The element was divided into 36166 by using 55789 central units. Injector inflicted pressure of 160 MPa. Picture 3 shows tension pressure analysis in researched injector nozzle . The range of tensions is between 44694 N/m² and 9,01461e+0,008 N/m². Plastic limit is 785593984 N/m².


**Fig. 3.** Tension pressure analysis

Picture 4 shows transfer pressure analysis in researched injector nozzle . The range of transfer is between 5.29954e-009 N·m and 0.000106048 N·m.


**Fig. 4.** Transfer pressure analysis

Picture 5 shows elastic strain pressure analysis in researched injector nozzle. The range of elastic strain was about 0,0001 Nm.

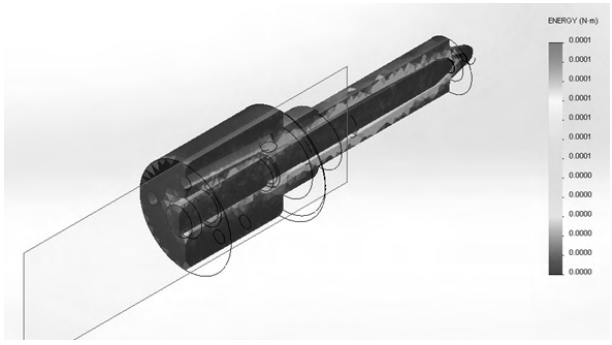


**Fig. 5.** Elastic strain pressure analysis

## THERMAL PHENOMENA OCCURING IN INJECTOR NOZZLE

The aim of the analytical researches was determining the temperature inside fuel injector [11, 12].

In order to determine the fuel temperature during its flow in the multi-hole injector (Fig. 6) the equations of the heat transfer and fluid flow through the tubular channel were used and the heat exchange by conductivity was established [8, 9, 10]. Fuel characteristics:

- Fuel absolute weight $\gamma$= 840 kg/m³
- Specific heat c= 2140 J/kg·K
- Thermal conductivity $k$= 0,1433 J/m·s·K
- Heat transfer coefficient $\lambda$= 165 W/m²·K

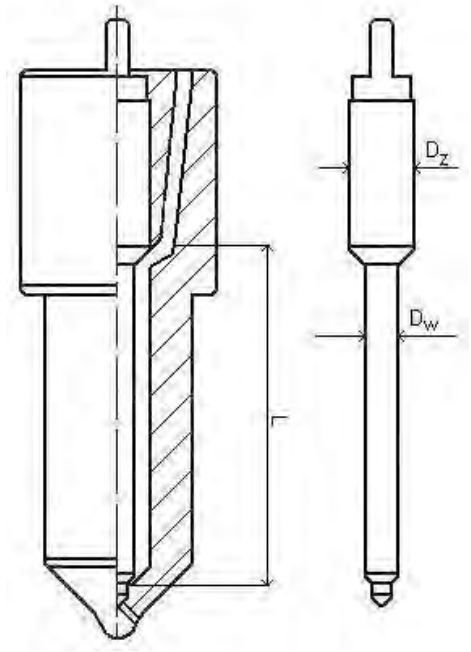


**Fig. 6.** Schematic of multi-hole injector

Injector characteristics:
$D_z$ = 0,005 [m],
$D_w$ = 0,0045 [m],
$L$ = 0,0 275 [m],
$g_v$ = 0,0000094 [m³/s].

Mathematical model of the multi-hole fuel injector proposed by the authors:
The duration of one cycle of the fuel injection [9]:

$$T_w = \frac{120}{n} \text{[s]}. \tag{1}$$

The volume of the fuel injected within one injection:

$$V_0 = T_w \cdot g_v \text{ [m³]}. \tag{2}$$

The fuel which flows around the injector needle forms a ring around it (in cross section). In order to facilitate the calculation of the heat exchange between the walls of the injector nozzle and the fuel, the conversion of the ring cross-section into a circular cross-section is necessary.

Cross-sectional area of the fuel pillar:

$$P_1 = \frac{\pi}{4}(D_z^2 - D_w^2) \text{ [m²]}. \tag{3}$$

Equivalent channel diameter:

$$D_1 = \sqrt{\frac{\pi}{4}P_1} \text{ [m]}. \tag{4}$$

Equivalent channel volume:

$$V_1 = P_1 \cdot L \text{ [m³]}. \tag{5}$$

The number of fuel doses per volume of the fuel injector nozzle channel:

$$j = \frac{V_0}{V_1}. \tag{6}$$

Fuel injection time:

$$\tau_w = \frac{\varphi}{720} T_w \text{ [s]}. \tag{7}$$

where: $\varphi$ – rotation angle of crankshaft.

Length of the segment corresponding to a dose of a specific fuel volume $l$:

$$l = \frac{L}{j} \text{ [m]}. \tag{8}$$

Lateral surface area of the liquid column of the length $l$ filling the channel $f$:

$$f = \pi \cdot D_1 \cdot l \text{ [m²]}. \tag{9}$$

The volume of the fuel pillar on the length $l$:

$$V_s = l \cdot P_1 \text{ [m³]}. \tag{10}$$

Fuel charge mass relating to the length $l$:

$$m = V_s \cdot \gamma \text{ [kg]}. \tag{11}$$

Fuel rate in the channel:

$$u = \frac{l}{\tau} \text{ [m/s]}. \tag{12}$$

Reynolds number:

$$Re = \frac{2D_l u}{\nu}. \tag{13}$$

To read the value of the kinematic viscosity in the graph (Fig. 2) the temperature of the fuel $T_0$ is needed:

$$T_0 = \frac{T_{pi} + T_{sci}}{2} \text{ [K]}. \tag{14}$$

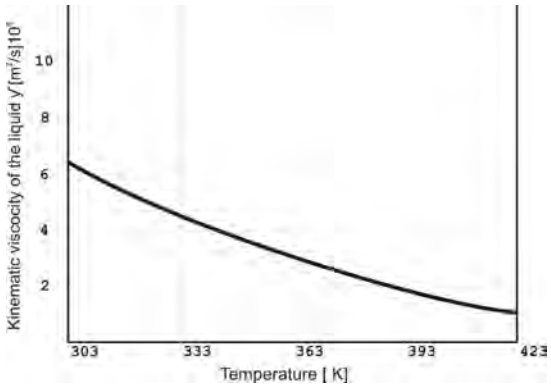


**Fig. 7.** Changing the viscosity of the fuel according to the temperature

Prandtl number for the fuel flowing into the channel section calculated by the arithmetic average of the temperature of the wall and fluid:

$$Pr = \frac{\nu \cdot c \cdot \gamma}{\lambda}. \tag{15}$$

Heat transfer coefficient of the flow through the channel:

$$\alpha_i = 0{,}023 \frac{\lambda}{2D_l} Re^{0{,}8} \, Pr^{0{,}4}. \tag{16}$$

Factor related to the geometry of the channel:

$$\eta = \frac{2}{D_1}. \tag{17}$$

Factor related to the physical properties of the fuel flow:

$$\beta_i = \frac{\alpha_i}{c \cdot \lambda \cdot u}. \tag{18}$$

Factor related to the heat transfer coefficient between the wall of the atomizer and the fuel flowing into the channel [14, 15, 16, 17, 18]:

$$\Theta = 0{,}9993 \cdot e^{-2\eta\beta_i}. \tag{19}$$

The fuel temperature after the flow through the selected channel segment:

$$T_{dyni} = T_{sci} - \Theta \cdot (T_{sci} - T_{pi}) \text{ [K]}. \tag{20}$$

The amount of heat supplied to the fuel during its stay in the atomizer channel:

$$\bar{Q} = \bar{k} \cdot \bar{f} \cdot (T_{sci} - T_{pi}) \cdot (T_w - \tau_w) \text{ [J]}. \tag{21}$$

Increase in fuel temperature during the downtime on the selected section of the channel [19, 20]:

$$\Delta T_i = \frac{Q_i}{m \cdot c} \text{ [K]}. \tag{22}$$

The final temperature of the fuel at the outlet from the selected section of the channel $t_{ki}$:

$$T_{ki} = T_{dyni} + \Delta T_i \text{ [K]}. \tag{23}$$

Growth of the fuel temperature over the entire length of the channel:

$$\Delta T_k = T_{ki} - T_{pi} \text{ [K]}. \tag{24}$$

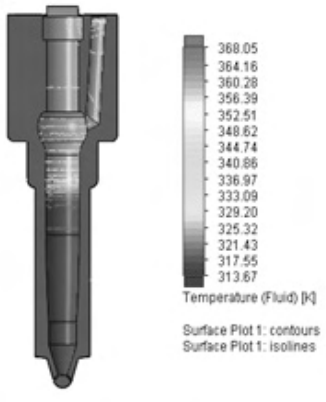


**Fig. 8.** Decomposition of fuel temperatures in injector nozzle

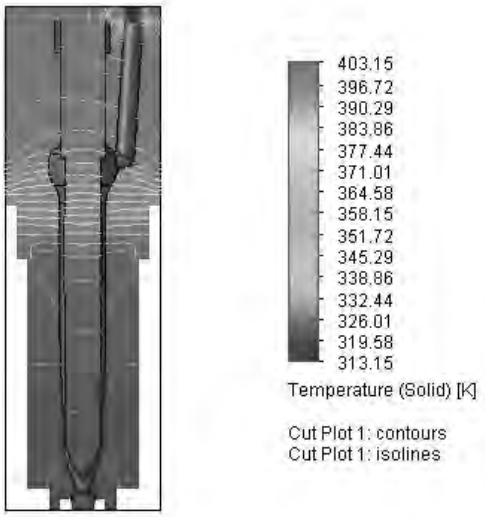


**Fig. 9.** Decomposition of surface temperatures outside the injector

## CONCLUSIONS

The carried out analysis showed pressure and temperature phenomena in a Diesel injector nozzle. Theoretical researches showed the fuel and surface temperatures distributions in a Diesel injector nozzle. Static elastic strain was about 0,001 Nm. The highest transfer and tension pressure was in the lower part of injector. The highest temperature inside nozzle surface was about 403 K surrounding the lower part. This part was placed in the combustion chamber. Fuel temperature reached about 368 K there. High pressures and temperatures generated huge tensions inside the nozzle during its work. These phenomena support the using of precision vapour in the nozzle needle. It is very important to supply engine with clean fuel. Every pollution damages injector spare parts and increases tension inside the nozzle[1].

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## ZJAWISKA FIZYCZNE ZACHODZĄCE W ROZPYLACZU WTRYSKIWACZA PALIWA SILNIKA ZS

**Streszczenie.** Artykuł opisuje zjawiska fizyczne występujące w rozpylaczu paliwa silnika z zapłonem samoczynnym. Świat wewnątrz wtryskiwacza paliwa należy postrzegać jako mikro. Zjawiska fizyczne zachodzące wewnątrz rozpylacza dotyczą bardzo wysokich ciśnień i temperatur, zjawisk balistycznych i burzliwego ponaddźwiękowego przepływu cieczy. Czynniki te wpływają na przyśpieszone zużycie elementów pary precyzyjnej iglicy rozpylacza i wpływają na jego pracę. Artykuł przedstawia w jaki sposób ciśnienie wpływa na naprężenia wewnątrz rozpylacza i pokazuje panujące tam warunki temperaturowe.

**Słowa kluczowe:** silnik z zapłonem samoczynnym, wtryskiwacz paliwa, rozpylacz paliwa, ciśnienie i temperatura.

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# Evaluation of Modern Diesel Engine Fuel Injectors

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**Summary.** The article describes methods of evaluation of modern Diesel engine fuel injectors. The analysis was carried out in a specialist laboratory taking up researching and repairing injection systems in combustion engines. The subject of scientific study was Bosch electromagnetic Diesel engine injector with a catalogue number 0445110083. The scientific object was evaluated and verified. There was made the microscopic specification sheet of elements exposed to wear and tear and tests were performed.
**Key words:** Diesel engine, fuel injector, Common Rail system, engine evaluation and repair.

## INTRODUCTION

Diesel engine fuel injection is used to distribute and spray fuel in combustion chamber. High pressures and temperatures inside engine cause disruptions in its correct work due to overstrains [5, 7].

At present in Common Rail systems electromagnetic and piezoelectric injectors are applied [11]. Electromagnetic injectors were introduced in 1997 and have been used successfully till the present time. The largest producer of Diesel system injectors in the world is Bosch company. Bosch company makes the following injectors of Common Rail system [11]. Electromagnetic are 1.0; 2.0; 2.1; 2.2 generations: as well as 2.5 and piezoelectric 1; 2; 3. Nowadays fully repairing are: 1.0; 2.0; 2.1; 2.2 generations [17, 18]. Generation 2.5 and all piezoelectric injection could not be repaired because of shortage technology and originals spare parts [6]. However there is a possibility to diagnose them. The others producers of Common Rail piezoelectric and electromagnetic injectors are Delphi and Denso only piezoelectric Continental – Siemens [12, 13, 15]. Delphi electromagnetic injectors are completely repaired whereas Denso because of shortage of original spare parts are partly repaired. Bosch, Delphi and Denso piezoelectric injectors could not be repaired nowadays because of shortage of technology and original spare parts [14, 19]. There are producers on the market who sell substitution parts but it is made with low quality. Siemens piezoelectric injectors are fully available to repair and to diagnose. It is possible to regulate them. There is only one problem with access to spare parts and information of instruction database [3, 8].

Generally piezoelectric injectors could be cleaned on the surface and thermo-chemically internally with the help of special detergent and next they can be diagnosed. Because of unreliability of piezoelectric crystals producers started removing them and coming back to electromagnetic injectors of modern generations.

## THE RULE OF COMMON RAIL ELECTROMAGNETIC INJECTOR'S OPERATION

Picture 1 presents the rule of Common Rail electromagnetic injector's work.

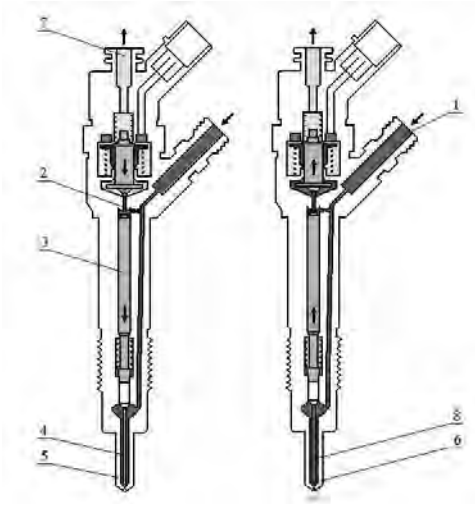



**Fig. 1.** The rule of Common Rail electromagnetic injector's work

Fuel is supplied to injector under high pressure by inlet pipe screwed to injector body whose magnitude depends on engine load and rotation speed. Next, it flows through inlet channel (1) through the body of injector to atomizer and combine channel (2) with steering chamber of injector work. If the pressure in valve chamber and in atomizer is the same at the time, the ending part of atomizer (6) is closed and injector does not break up into a spray into combustion chamber. But when coil obtains voltage under the influence of electromagnetic field, raises unit shaft is raised and the valve starts to open (2). A the time difference of pressure appears in the lower and upper part of injector. Higher pressure in the nozzle causes lifts the needle (8) and begins injection of fuel to the combustion chamber. When the voltage disappears in the coil unit shaft comes back to the down position and closes the steering injector valve. Pressure in lower and upper part of the injector adjustment and the needle under pressure the spring closes nozzle and finishes work of the injector.

## METHODS OF DIAGNOSING MODERN FUEL INJECTORS AND THEIR PROBLEMS

Diagnose process of modern fuel injectors begins already in the vehicle with working engine. There are researched two parameters: dosage compensation on every cylinder and dosage return magnitude on neutral gear. Engine parameters on neutral gear are the injection fuel pressure between 25 – 30 MPa and injection time from 250 μs for pilots dosage to circa 800 μs for main dosage. These conditions are ideal to make diagnose of injector. With low pressures and injection times the first symptoms of faulty operation can be noticed. B reconstruction analysis of dosage compensation it can be determined which injector gives more fuel and which less. Too big differences between injectors indicate that it should be dismantled and diagnosed. Return dosage is discharge of working fluid during injector work. Every well-working injector has the determined value of it. If the discharge values are higher than the established standards it means that separate spare parts and seals are damaged and they should be replaced or repaired if it is possible.

Second stage of evaluating fuel injectors should be made in a special laboratory with suitable equipment. The first is cleaning injector nozzle in the sonic washer and installation of injector to the testing machine in order to research fluid tightness, injection and return dosage as well as the spraying stream of fuel. It should be remarked that all the injectors have to be taken out from the engine because in another situation our diagnose will be faulty. Research on the testing machine shows which injector works incorrectly.

The third stage of diagnose relies on the disassembly of the injector into spare parts, analysis under microscope, washing all elements in ultrasonic washer, their assembly according to special procedures, their regulation and, finally, research on the testing machine. It should be remembered that even if only one injector differs from another it has to be taken out, examined under microscope and cleaned in sonic washer [16, 18]. Then we will be sure that the verification process and eventual repair were correct. A very important element during the research is verification using a microscope. It allows us to check if there are some iron filings inside the injector coming from high pressure in the injection pump [1, 2].

The greatest number of malfunctions of fuel injectors occur in the surface of precision vapour needle injector piston, steering valve, nozzle and insulation [9, 10, 20].

## THE AIM AND SCOPE OF EXPERIMENTAL RESEARCH

Experimental research concerned diagnose of electromagnetic Bosch Common Rail injector with catalog number 0445110083. The aim of researches was to make correct diagnose and eventually regeneration process of the researched injector. Researches were made by using special instruments and testing machines in a laboratory research unit and then repairing injection systems of combustion engines.

## CHARACTERISTICS OF RESEARCH OBJECT AND WORKSTATION

The research object was Common Rail electromagnetic Bosch injector generation 1.0 with catalog number 0445110083. Picture 2 shows the disassemble of the injector into spare parts.

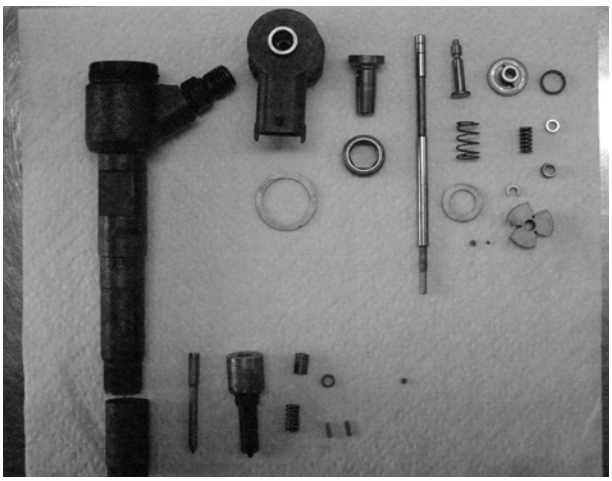


**Fig. 2.** Electromagnetic Bosch generation 1.0 injector disassembled into spare parts

Laboratory researches were made by using test machine STPiW 3 and stereoscope microscope. On the testing machine injection dosage and discharge were measured and visual condition of spare parts responsible for the injector's correct work was examined by using a microscope. Picture 3 shows STPiW 3 testing machine as the workstation of researches.

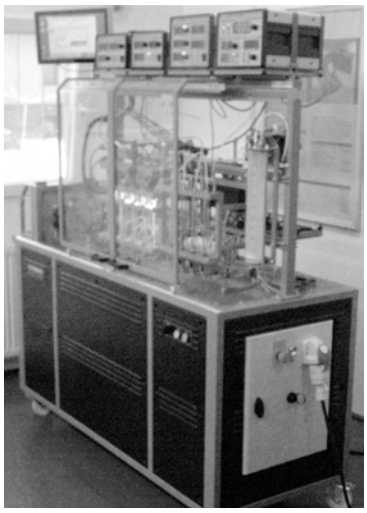
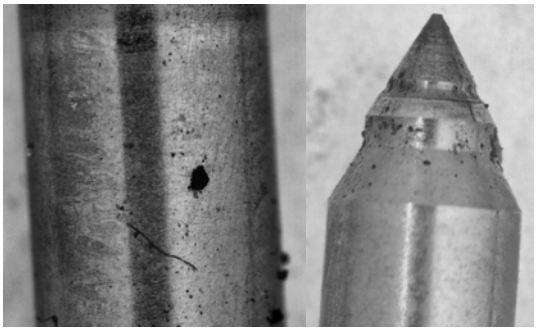


**Fig. 3.** Research workstation

## RESEARCH RESULTS

Experimental researches were made according to the following procedure: the injector was disassembled into spare parts and subjected to verification by using stereoscope microscope. Picture 4 shows elements of needle precision vapour which open and close at fuel spraying. There are visible marks of intensive wear of the vapour stream nozzle in picture 4a. It is easy to notice little marks of corrosion in picture 4b but it has no influence on nozzle work [20]. As it can be visible in the picture, the needle is a little bit dirty with wastes coming from fuel. There are no marks of metal filings.



a) b)

**Fig. 4a.** Element of injector precision vapour, **b)** Injector nozzle needle

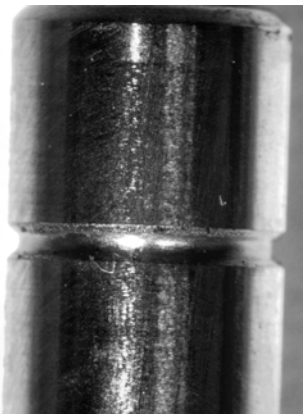


**Fig. 5.** Piston precision vapour steering valve of fuel injector

There is the element of piston steering injector valve precision vapour in picture 5. The dark surface means intensive use of precision vapour element. It has influence on the amount of fuel discharge.

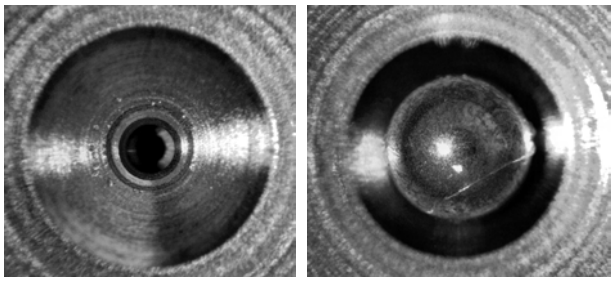


**Fig. 6.** Steering valve of Common Rail Bosch injector – left without a ball, right with a ball

Picture 6 presents a section of steering valve electromagnetic Common Rail Bosch injector. It shows the section without a ball in picture 6a and the section with a ball in picture 6b. Steering valve is in good condition. Picture 6b shows the steering valve with the ball – as it is visible the ball fits well to the section, which has a huge influence on good fuel injection work.

Table 1 shows injection and return dosage values researched in the injector and work parameters during a test. The test was made for variable injection times and pressures. Test 1 concerns tightness research of injector and discharge value at not working nozzle for the pressure 145 MPa. Time test was 60 seconds. Test 2 is a check of full load dosage. During this probe the researched parameters are injection dosage and discharge by 135 MPa pressure (maximum work pressure of these injector) and injection time 720 µs. Another test was research of neutral gear dosage by 30 MPa injection pressure and 420 µs injection time. The last test was pilot dosage. It is characteristic for this research that low pressure about 30 MPa and small injection time 250 µs were applied. If this dosage is dropping it means that the injector should be repair. This dosage accounts for detonation combustion on neutral gear.

**Table 1.** Results of researches on injection dosage and discharge using the testing machine

| | MPa | µs | mm³/H | | Injector 1 |
|---|---|---|---|---|---|
| | | | | Catalog no | 0445110083 |
| No | Injection pressure | Injection time | Range | | |
| 1 | 145 | 60 s | 0,00 – 0,00 | Dosage | 0,0 |
| | | | 0,00 – 72,00 | Discharge | 34,1 |
| 2 | 135 | 780 | 34,71 – 49,69 | Dosage | 46,6 |
| | | | 16,00 – 58,00 | Discharge | 32,3 |
| 3 | 30 | 420 | 0,31 – 3,89 | Dosage | 1,9 |
| | | | 0,00 – 58,00 | Discharge | 7,1 |
| 4 | 80 | 260 | 0,31 – 4,09 | Dosage | 2,4 |
| | | | 0,00 – 58,00 | Discharge | 9,0 |
| Test pass | | | | | Yes |

Additional test is injector work characteristics made on STPiW 3 testing machine. It shows an outlay of all dosages

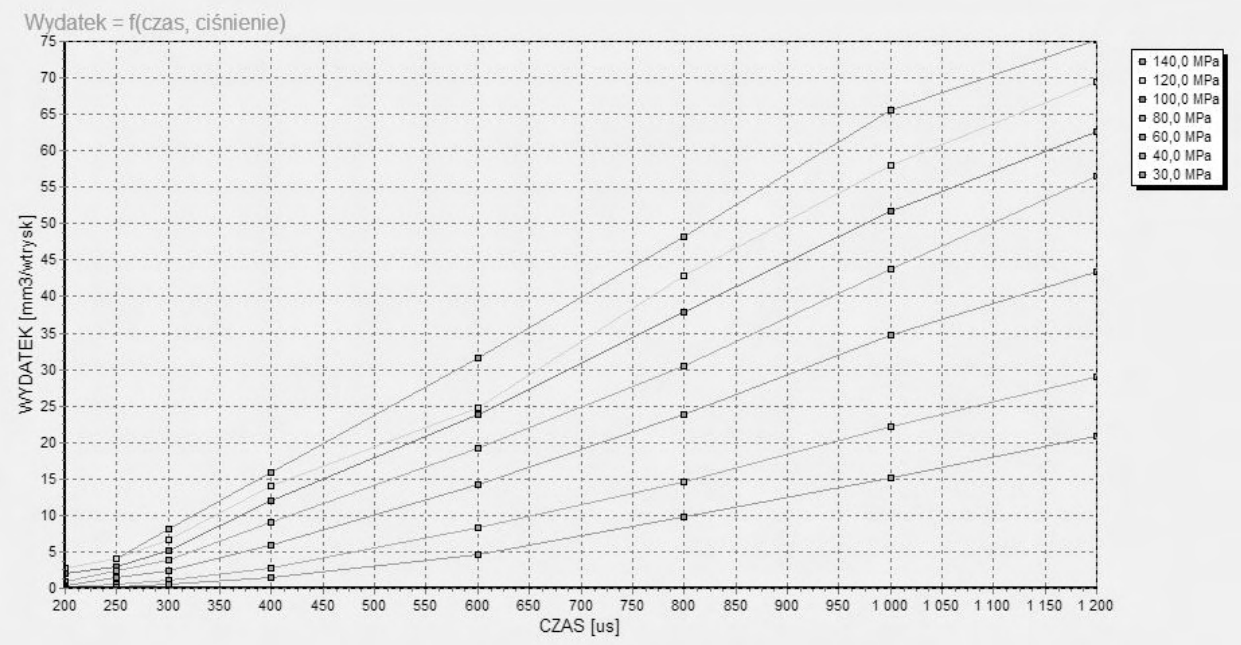



**Fig. 7.** Characteristic of the researched injector on testing machine

at various pressures and injection times. The characteristics is useful because it can be compared to all injectors in the engine in the whole range of work. Beginning from micro dosages and ending on full load with maximum injection times and pressures. Picture 7 presents full research on Bosch fuel injector characteristic with catalog number 0445110083.

## CONCLUSION

The analysis of the carried out diagnose shows that researched fuel injector retained its own work parameters. The pictures made during microscope researches showed elements of steering valve and precision vapour after short use. Theoretically, these spare parts should be replaced with new ones, judging from the pictures. But tightness dosages and discharges tests showed that in spite of cavity wear of spare parts, the injector has all the working parameters correct. It means that it can be recognized as capable of good operation. Worrying is the fact of appearance of metal filings on valve surface steering in the injection work picture 5a. It means that the whole injection system should be disassembled, cleaned and dismantled and the height of pressure pump checked because metal filings come from it.

One reason of faster injectors damages are uses of high pressure pumps which soil the whole injection system with metal filings. Sometimes these filings are so small that they are not caught by fuel filter.

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## DIAGNOZOWANIE WSPÓŁCZESNYCH WTRYSKIWACZY PALIWA W SILNIKACH Z ZAPŁONEM SAMOCZYNNYM

**Streszczenie.** Artykuł przedstawia sposoby diagnozowania współczesnych wtryskiwaczy paliwa silnika z zapłonem samoczynnym. Analiza została wykonana w specjalistycznym laboratorium zajmującym się badaniem i regeneracją układów wtryskowych silników spalinowych. Obiektem badawczym był wtryskiwacz elektromagnetyczny firmy Bosch o nr katalogowym 0445 110 083. Badany obiekt przeszedł całkowity proces diagnozy i weryfikacji. Wykonano dokumentację mikroskopową elementów narażonych na zużycie oraz wykonano testy poprawnego funkcjonowania na stołach probierczych.
**Słowa kluczowe:** silnik spalinowy, wtryskiwacz paliwa, układ Common Rail, regeneracja wtryskiwaczy paliwa, diagnozowanie układów Common Rail.

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# Evaluation of Water Vapor Permeability of Biodegradable Starch-Based Films

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**Summary.** Packaging is an integral part of food – meets both security features to packaged food and marketing to encourage potential consumers to purchase. In the era of sustainable development, which produced materials to be environmentally friendly, a lot of attention is paid to the biodegradable packaging. The aim of this study was to evaluate the water vapor permeability of starch films on the basis of gravimetric method. Permeability tests were performed for various compositions of raw materials and processed at different screw speeds during film blowing. Tests results showed that water vapor permeability values ranged from $2{,}63 \cdot 10^{-9}$ to $0{,}65 \cdot 10^{-9}$ g/(m·s·Pa) depending on recipe of granulate and processing conditions. Lower permeability of water vapor occurred in starch film with 20% of glycerol and 4% of poly(vinyl) alcohol processed at 80 rpm.
**Key words:** starch, biodegradable packaging, film blowing, water vapor permeability.

## INTRODUCTION

Packaging material is an integral part of food products which has to fulfil a number of important functions. First of all, it is to protect the product, facilitate storage and sale. Packaging should prevent spoilage, discoloration, contamination or damage of the product. In view of the widespread use of plastics and because of the environmental problems there are increasingly higher requirements for the packaging to be "environmentally friendly". For this purpose, some additional agents can be easily incorporated into the packaging materials or biodegradable plastics are designed, which are able to degrade in a short time [3, 21]. However, due to the food safety, these materials require the detailed research for their quality and properties.

Popularity of plastics as packaging materials for food is the result of beneficial properties, such as the mechanical tensile strength, high barrier properties against oxygen, carbon dioxide, anhydrides and aromas or good sealing features. Used over the years synthetic plastics have led to serious environmental problems. At the same time such a situation led to intensive research on the development of biodegradable materials.

For biodegradable packaging materials from renewable resources starch is primarily applied [1, 14, 16, 18]. However, if the biodegradable materials are designed to be used as food packaging they must meet the requirements for materials intended for contact with food. These concerns mainly the protection of the product from physical damage, contamination or deterioration and the maintaining of the quality of the product. From the viewpoint of the packaging industry, starch-based materials have an enormous potential due to the biodegradability, compostability, but also the availability of large quantities of starch and its renewability [3, 4, 15]. Furthermore, due to their relatively low cost, they could be an attractive alternative to polymers based on petrochemical raw materials [22]. Starch-based packaging materials have been used as films for wrapping food, food containers such as bowls, plates, cups, egg wrappings. Thermoplastic starch has good oxygen barrier properties, but the hygroscopic nature of starch makes this material unsuitable for liquid products and for high-moisture food [5, 9, 18, 20, 23].

The aim of the study was to determine the water vapor permeability of starch-based films with different additives depending on granulates composition and film-blowing conditions.

## MATERIALS AND METHODS

The scope of work included measuring the water vapor permeability of biodegradable starch-based films with gravimetric method. The material used in experiments included the starch-based biodegradable films, processed from granulates with composition shown in Table 1. The films were produced at the Department of Process Engineering, Faculty of Production Engineering, University of Life Sciences in

Lublin in the two-step process: biopolymer granulates were processed using the extrusion-cooking equipment, and the films were made from granulates using film-blowing device at various screw rotational speed of 50, 60, 70 and 80 rpm, depending on the granulates applied [18]. Water vapor permeability through the packaging starch-based material was tested in the Department of Food Engineering and Process Management, Faculty of Food Sciences, SGGW in Warsaw using gravimetric method described by Jamshidian and coworkers [8].

The films were placed between two gaskets and sealed in specially prepared glass containers with an opening and twist-off cap. Glass containers were filled with distilled water, which has a water activity equal to 1 and 3167 Pa pressure. Measuring containers were placed in a desiccator with a solution of $MgCl_2$ for conditions ensuring constant relative humidity at 30%. The testing was carried out at room temperature. Measurements of the sample mass were performed once a day for 7 days. The tests were performed in duplicate. To determine the permeability it was necessary to perform film thickness measurement, which was realized using the thickness gauge A400 Ultrametr Metrison with accuracy of 1 micron. The measurement was performed in six replicates.

Water vapor permeability was calculated from the formula:

$$P = \frac{\Delta m \cdot e}{A \cdot \Delta t \cdot \Delta p}, \quad (1)$$

where:

P – water vapor permeability, g/(m·s·Pa),

$\Delta m/\Delta t$ – sample weight loss in time function , g/s,

e – film thickness, m,

A – permeability area, $8.55 \cdot 10^{-4}$ m²,

$\Delta p$ – pressure difference under the film and outside, Pa.

Changes of sample mass during the time were calculated by use of linear regression. The data were analyzed by ANOVA using Statgraphics Plus 4.1 software. Fishers test was used for the analysis. Verification was made at the significance level of 0.05 [11]. An analysis of the detailed comparisons was performed at the significance level $\alpha$ = 0.05, which divided the means of results into homogeneous groups.

**Table 1.** Composition of starch films

| Lp. | Material* | Potato starch [%] | Glycerol [%] | Poly(vinyl) alcohol [%] | Keratin [%] | Flax oil [%] |
|---|---|---|---|---|---|---|
| 1 | SGA I | 78.0 | 20 | 2.0 | - | - |
| 2 | SGA II | 76.0 | 20 | 4.0 | - | - |
| 3 | SGA III | 74.0 | 20 | 6.0 | - | - |
| 4 | SGAK II | 77.0 | 20 | 2.0 | 1.0 | - |
| 5 | SGAK III | 76.0 | 20 | 3.0 | 1.0 | - |
| 6 | SGAK IV | 75.5 | 20 | 3.5 | 1.0 | - |
| 7 | SGK III | 79.75 | 20 | - | 0.25 | - |
| 8 | SGO II | 78.5 | 20 | - | - | 1.5 |

* symbol explanation:

S – potato starch K – keratin

A – poly(vinyl) alcohol O – flax oil

## RESULTS

One function of packaging materials is the formation of barrier for water between the food and the environment. It was observed that before the expiry of seven days of research, some attempts of starchy materials have been overgrown with mold such as SGA II 80, SGA III 80, SGK III 60, SGK III 50, SGK III 70, SGAK III 70. A similar phenomenon was observed for starch films by Bergenholtz and Nielsen [2].

Figure 1 shows the water vapor permeability results of SGA films containing starch with addition of poly(vinyl) alcohol. Permeability for this group of materials varied in the range of $0.65^{\cdot 10^{-9}}$ for the SGA II 80 to $2.63^{\cdot 10^{-9}}$ g/(m·s·Pa) for the SGA I 80. Increasing the content of poly(vinyl) alcohol from 2 up to 4% resulted in a 4-fold reduction in the water vapor permeability of film processed at 80 rpm, and almost three times using 50 rpm during film-blowing of starch granulates with this agent.

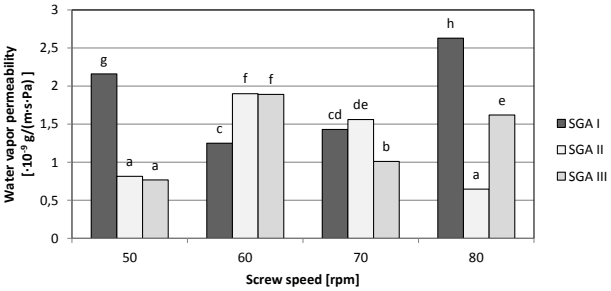


**Fig. 1.** Water vapor permeability of starch films SGA processed with film-blowing at various screw speed (numbers I, II, III marked poly(vinyl) alcohol amount: 2, 4 and 6%, respectively); a – h – similar letters showed homogeneous groups of means

Also for starch-based films SGAK with the addition of poly(vinyl) alcohol and keratin diversified results were obtained (Fig. 2). The material, which was characterized by the highest permeability with mean result of $2.29 \cdot 10^{-9}$ g/(m·s·Pa) was film processed with SGAK IV recipe using 80 rpm during film-blowing. In contrast, the film prepared from the same recipe but processed using 60 rpm screw speed was characterized by the lowest water vapor permeability at the level of $0.72 \cdot 10^{-9}$ g/(m·s·Pa).

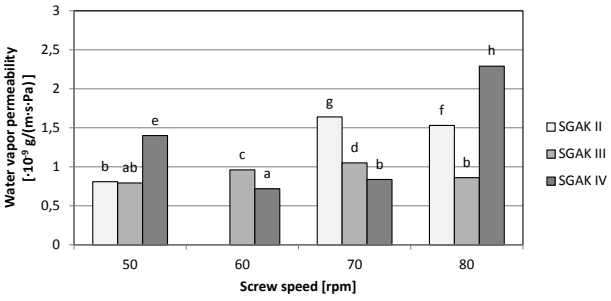


**Fig. 2.** Water vapor permeability of starch films SGAK processed with film-blowing at various screw speed (numbers II, III, IV marked poly(vinyl) alcohol amount: 2, 3 and 3.5%, respectively, K is 1% of keratin); a – h – similar letters showed homogeneous groups of means

During the tests of film materials containing starch and addition of keratin (the material symbol SGK), the lowest permeability ($0.778 \cdot 10^{-9}$ g/(m·s·Pa) was evaluated for the material processed at 70 rpm screw speed (Fig. 3). For the same screw speed applied during film-blowing of SGO material with flaxseed oil addition also low permeability at the level of $0.889 \cdot 10^{-9}$ g/(m·s·Pa) was determined.

Analysis of the results presented in the paper showed statistically significant differences in water vapor permeability between samples (Tab. 2).

Both the material composition and the processing conditions affected the level of water vapor permeability. There was no linear relationship between the number of screw speed used in the production of starch-based films and the level of water vapor permeability. Additionally, it was shown that both the formulation and production parameters could affect the film water vapor permeability. It was noted that even a small addition of substances such as 0.25% of keratin or up to 6% of poly(vinyl) alcohol, and variation in screw speed during starch-based film processing can cause significant changes in water vapor permeability of the packaging. The appropriate selection of additives for the preparation of raw material mixtures and proper selection of production parameters can produce a film with satisfactory parameters of permeability.

Confirmation of significantly altering the barrier to water vapor by the addition of various substances are tests results presented by Galdeano et al. [7], who conducted the study of the oat starch film produced by casting with the addition of various plasticizers: glycerol, sorbitol, and mixtures of glycerol, sorbitol, sucrose and urea. It was shown that the water vapor permeability (WVP) of the film with the addition of the plasticizer was significantly lower than without the additive. Plasticizers prevent cracking of the film during cargo handling and storage, but their greater additive reduces the barrier to gases, water vapor and solutes. This behavior is probably due to the structural modification of the starch, which may become less dense, due to the addition of substances with hydrophilic character which promote absorption and desorption of water [1].

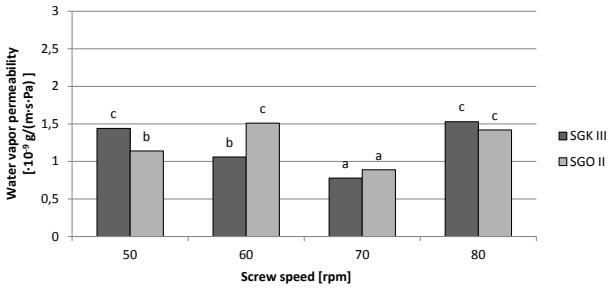


**Fig. 3.** Water vapor permeability of starch films SGK and SGO processed with film-blowing at various screw speed (K is 0.25% of keratin, O is 1.5% of flax oil); a – c – similar letters showed homogeneous groups of means

Galdeano et al. [6] observed the opposite situation, probably due to the antiplasticizing effect exerted by plasticizers used in specific experimental conditions in which they were tested. The values of water vapor permeability of plasticized films ranged from 2.317 to $4.211 \cdot 10^{-12}$ g/(m·s·Pa), whereby the lowest permeability was evaluated during tests of film with sucrose addition. Sucrose molecules, as a result of crystal formation, influenced the film matrix and increased the barrier properties [24]. In contrast, the highest permeability was obtained for film with glycerol, as expected. Glycerol is an effective plasticizer having high ability to interact with water, facilitating its solubility and penetration through the membrane [12]. This is so, because of easy penetration of glycerol inside the film structure and the presence of hydroxyl groups, thereby producing a highly hydrophilic material [13].

**Table. 2.** Analysis of variance of water vapor permeability results of starch-based films

| Source of variation SGA | Degree of freedom df | Mean square MS | F | p-value |
|---|---|---|---|---|
| Between groups | 11 | 0 | 104,54 | 0,0000 |
| Inside groups (error) | 12 | 0 | | |
| Total | 23 | | | |
| Source of variation SGAK | Degree of freedom df | Mean square MS | F | p-value |
| Between groups | 10 | 0 | 320,04 | 0,0000 |
| Inside groups (error) | 11 | 0 | | |
| Total | 21 | | | |
| Source of variation SGK | Degree of freedom df | Mean square MS | F | p-value |
| Between groups | 3 | 0 | 107,64 | 0,0003 |
| Inside groups (error) | 4 | 0 | | |
| Total | 7 | | | |
| Source of variation SGO | Degree of freedom df | Mean square MS | F | p-value |
| Between groups | 3 | 0 | 128,43 | 0,0002 |
| Inside groups (error) | 4 | 0 | | |
| Total | 7 | | | |

According to the results presented by Sobral and coworkers [19] the more plasticizer is used, the lesser density of network is formed and consequently the film is more permeable. The value obtained by these authors for film with glycerol was lower than that of starch materials tested with various additional substances. This may be due to various origins of the starch or additional substances, which caused an increase in permeability. An increased lipid content in oat may help to reduce the water vapor permeability of the film, presumably because lipids influence the barrier properties.

Similarly, Kechichian and coworkers [10] showed that the addition of antimicrobial constituents significantly affects the properties of the film based on manioc starch produced by casting. Films with the average content of cinnamon powder (0.2 g/100g) presented the lowest value of the water vapor permeability (WVP), probably because these components affect the improvement of barrier to water vapor of biodegradable film matrix. Addition of more antibacterial component caused the opposite effect and water vapor permeability (WVP) increased, which indicates that there is limited range of application of this additive to improve the barrier properties against water vapor.

Comparing the results for starch-based materials with literature data for the film produced on the basis of petroleum raw materials, or for some biopolymers, it can be stated that the starch-based materials have a lower barrier properties. Presented in this study potato starch-based films were characterized by low water vapor permeability, i.e. SGA II 80, received a similar value as for materials with manioc starch plasticized with glycerol (40g/100g of starch) – $6.25 \cdot 10^{-10}$ g/(m·s·Pa) and maize starch plasticized with glycerol (40g/100g of starch) – $6.7 \cdot 10^{-10}$ g/m·s·Pa [12]. The film prepared with low density polyethylene LDPE exhibits higher barrier properties with values of water vapor permeability from $0.9 \cdot 10^{-12}$ to $1.3 \cdot 10^{-12}$ g/(m·s·Pa) [17].

## CONCLUSIONS

Starch-based biodegradable materials with the addition of glycerol, poly(vinyl) alcohol, keratin and flax oil tested in this work failed to meet the requirements for the food contact packaging materials. During the water vapor permeability tests absorption of water vapor was observed, and thus the use of such packages in contact with food is unsuitable. Water vapor permeability of starch-based packaging materials ranged from $2.63^{\cdot 10^{-9}}$ to $0.65^{\cdot 10^{-9}}$ g/(m·s·Pa). The lowest water vapor permeability was evaluated for SGA II 80 – potato starch-based film containing 20% of glycerol and 4% of poly(vinyl) alcohol addition, processed with film-blowing at 80 rpm screw rotational speed.

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## OCENA PRZEPUSZCZALNOŚCI PARY WODNEJ SKROBIOWYCH FOLII BIODEGRADOWALNYCH

**Streszczenie.** Opakowanie stanowi nieodłączny element żywności – spełnia zarówno funkcje ochronne wobec zapakowanej żywności, jak i marketingowe, mające zachęcić potencjalnego konsumenta do zakupu. W dobie zrównoważonego rozwoju, gdzie wytwarzane materiały mają być przyjazne środowisku, wiele uwagi poświęca się opakowaniom biodegradowalnym. Celem pracy było określenie przepuszczalności pary wodnej materiałów przyjaznych środowisku w oparciu o metodę grawimetryczną. W pracy badano przepuszczalność pary wodnej folii skrobiowych wykonanych z różnych mieszanek surowcowych oraz z zastosowaniem zróżnicowanych obrotów ślimaka podczas wytłaczania folii z rozdmuchem. Przeprowadzone badania wykazały, że przepuszczalność pary wodnej dla opakowań skrobiowych wynosiła od $2{,}63 \cdot 10^{-9}$ do $0{,}65 \cdot 10^{-9}$ g/(m·s·Pa). Najniższą przepuszczalnością wobec pary wodnej charakteryzowała się folia skrobiowa z 20% zawartością gliceryny oraz 4% dodatkiem alkoholu poliwinylowego wyprodukowana przy prędkości obrotowej ślimaka 80 obr·min$^{-1}$.
**Słowa kluczowe:** skrobia, wytłaczanie, opakowania biodegradowalne, przepuszczalność pary wodnej**.**

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# Investigations Into the Process of Rotary Mowing of Selected Energy Crops

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**Summary.** The paper discusses the influence of plant moisture and linear and rotational speeds of the blades of a rotary cutting assembly on the unit energy needed for cutting the stems of Virginia Mallow (Sida Hermaphrodita) and Miscanthus giganteus. The optimum operating parameters of the rotary cutting assembly have been selected in terms of minimum energy demand in the cutting process of the said crops.

**Key words:** Virginia Mallow, Miscanthus Giganteus, cutting process, energy crops, unit cutting energy, moisture, linear speed of the cutting assembly, rotational speed of the cutting assembly.

## INTRODUCTION

Biomass, aside from solar energy and wind, is considered the most important source of renewable energy on our planet [3, 7, 8]. The most popular and most widely explored plant for the production of biomass is willow [1, 4, 5, 9, 21, 23, 24]. Other energy plants are also worth attention, since their cultivation under certain conditions may render similar or even better results [2]. Such plants are Virginia Mallow and Miscanthus Giganteus.

Mowing of the plant shoots can be done upon vegetation, when the leaves fall. The end of the cutting period should take place prior to new vegetation. In practice, harvesting is performed manually or using mower systems from half of November until the end of March [6, 11]. In the case of Virginia Mallow or Miscanthus giganteus grown on small plantations, classical mowing systems can be used (used in typical rotary mowers) [12, 13], which is why it is necessary to seek the most optimum operating parameters of the rotary cutting assembly in the cutting process of these plants [10, 15, 25]. The determination of these parameters will be possible upon an analysis of the results of the investigations conducted on a laboratory stand designed for tests of energy demand in the plant mowing process.

## THE RESEARCH AIM

The aim of the research was to find the optimum operating parameters of a rotary cutting assembly in terms of energy demand for the stem cutting process of Virginia Mallow and Miscanthus giganteus. The investigations were conducted for:

– different linear speeds of the cutting assembly,
– different rotational speeds of the cutting assembly,
– different moistures of the plant material.

The investigations were conducted on a laboratory test stand designed for testing rotary cutting of energy crops located in the Department of Mechanical Systems Engineering and Automation at the Institute of Mechanical Engineering, Warsaw University of Technology – the Płock Campus, as a continuation of research works conducted at this facility for many years [16, 17, 18, 19, 27, 28, 29].

## OBJECT OF THE RESEARCH

Energy crops are characterized by a rapid growth at the beginning of vegetation and a multitude of stems in the dry part of the supra-terrestrial part of the plant (its greater energy potential compared to leaves), low soil requirements and high yield of biomass [2]. Because of these factors, Virginia Mallow and Miscanthus giganteus were selected for the investigations.

Virginia Mallow was imported to Poland in the 1950s of the last century. It is highly resistant to severe soil and climate conditions. It multiplies generatively (through seeds) or through vegetation (plant seedlings). It grows to the height of up to 350 cm. From 1 ha of crop up to 250 GJ of energy can be obtained [22].

Miscanthus giganteus is a perennial grass built of rigid blades having a spongy core of the height reaching 300 cm (intense growth of mass). It is pest and disease resistant. It

does not grow on swamp and wet soils. It multiplies through vegetation (plant seedlings). From 1 ha of crop 300 GJ of energy can be obtained [22].

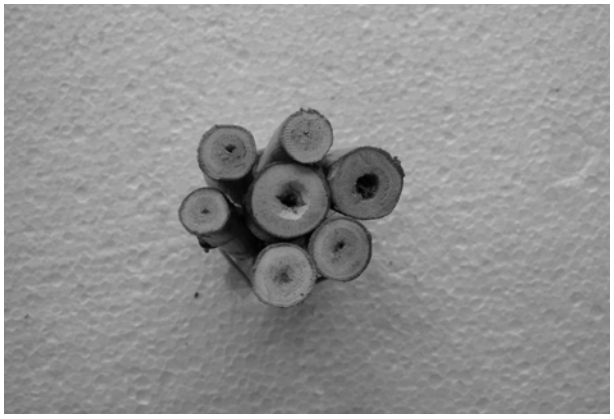

**Fig. 1.** Cross-section of the Stem of Virginia Mallow

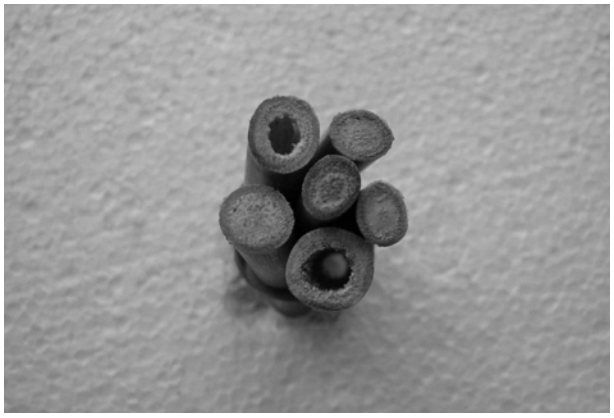

**Fig. 2.** Cross-section of the Stem of Miscanthus giganteus

## THE TEST STAND

The test stand includes a frame structure on which the cutting assembly taken from a classical rotary mower is fitted [20, 26]. The working disc of the cutting assembly has two symmetrical inertia blades fixed to blade holders. The rotary cutting assembly is driven by a three-phase electric motor. The motor is controlled by an inverter programmed from a PC. The mower movement is simulated by a progressive motion of a trolley carrying energy crops.

During the tests, the computer records the increase in the electric power consumption as a function of time and, on this basis, the unit energy demand to cut the energy crops is calculated. Unit energy for cutting is the total energy needed for the process of cutting per unit of cross-section area of the cut stems.

## METHODOLOGY AND COURSE OF THE TEST

Virginia Mallow and Miscanthus Giganteus were selected for the rotary cutting tests. The plants came from an experimental station at the Department of Agriculture and Biology at Warsaw University of Life Sciences (SGGW) in Skierniewice. Samples of the length of 250 mm were prepared from the stems of the energy plants. Then a selection in terms of moisture level was performed (20%, 40%, 60%). Such samples were fixed in the trolley simulating the motion of the cutting assembly under actual field conditions. The cross-section area of the mowed plant was 0.0038 m². Each measurement was repeated a minimum of three times [14]. The cutting of the plant was done under the following conditions:

- temperature 20 °C,
- ambient pressure 768 mm Hg,
- weight of the inertia blade m = 65.05 g,
- angle of the blade edge α = 29°20’,
- type of the blade edge: cut upwards,
- number of cutting blades: 2 blades located symmetrically on the circumference of the working disc,
- diameter of the working disc f = 680 mm,
- speed of the trolley simulating the linear motion of the cutting assembly: V=0.031 m/s, V=0.063 m/s, V=0.105 m/s,
- rotational speed of the cutting assembly: n= 1424,1824, 2108 rpm.

## RESULTS

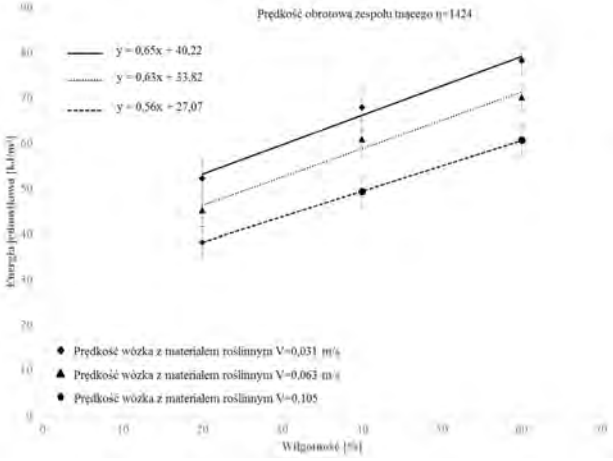


**Fig. 3.** Comparison of the course of changes of the unit cutting energy of Virginia Mallow as a function of moisture for 3 linear speeds of the trolley carrying the plant material at the rotational speed of the cutting assembly of n=1424 rpm.

Key:– unit energy [kJ/m2]; moisture – [%], speed of the cutting assembly – [rpm], · 5t speed of the trolley carrying the plant material [m/s]

The unit cutting energy of the Virginia Mallow as a function of moisture grows for each of the tested linear speeds of the trolley carrying the plant material (Fig. 3).

The greater the linear speed of the trolley carrying the plant material, the lower the unit cutting energy. A change in the linear speed of the trolley from 0.031 m/s to 0.063 m/s results in a drop of the unit cutting energy by 11 % on average and a further change of the speed from 0.063 m/s to 0.105 m/s results in a drop of the unit cutting energy by another 15 %.

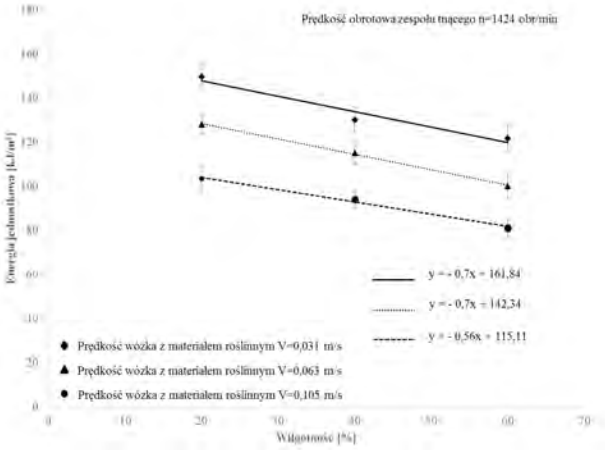


**Fig. 4.** Comparison of the course of changes of the unit cutting energy of Miscanthus giganteus as a function of moisture for 3 linear speeds of the trolley carrying the plant material at the rotational speed of the cutting assembly of n=1424 rpm.

The unit cutting energy of Miscanthus giganteus as a function of moisture decreases for each of the tested linear speeds of the trolley carrying the plant material (Fig. 4).

The greater the linear speed of the trolley carrying the plant material, the lower the unit cutting energy (Fig. 4). A change in the linear speed of the trolley from 0.031 m/s to 0.063 m/s results in a drop of the unit cutting energy by 19 %, on average and a further change in the speed from 0.063 m/s to 0.105 m/s results in a drop of the unit cutting energy by another 22 %, on average.

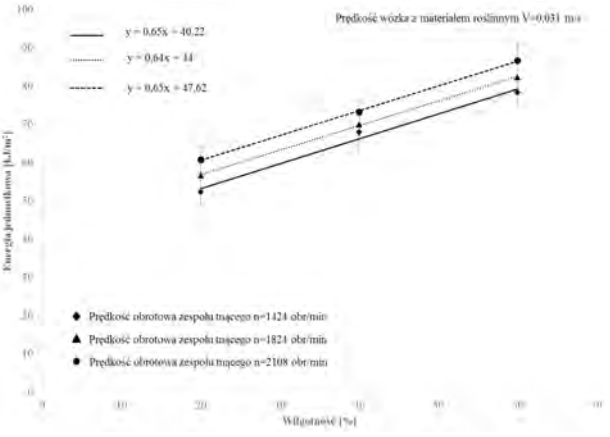


**Fig. 5.** Comparison of the course of changes of the unit cutting energy of Virginia Mallow as a function of moisture for 3 rotational speeds of the cutting assembly at the linear speed of the trolley carrying the plant material of V=0.031 m/s.

Key: unit energy [kJ/m²]; moisture [%]; speed of the trolley carrying the plant material [m/s]; · 5t rotational speed of the cutting assembly [rpm]

The unit cutting energy of Virginia Mallow as a function of moisture grows for each of the tested rotational speeds of the cutting assembly (Fig. 5).

The greater the rotational speed of the cutting assembly, the greater the unit cutting energy (Fig. 5). An increase in the rotational speed from 1424 rpm to 1824 rpm results in an increase in the unit cutting energy by 4% on average and a change from 1824 rpm to 2108 rpm results in a further increase in the cutting energy by 6 %, on average.

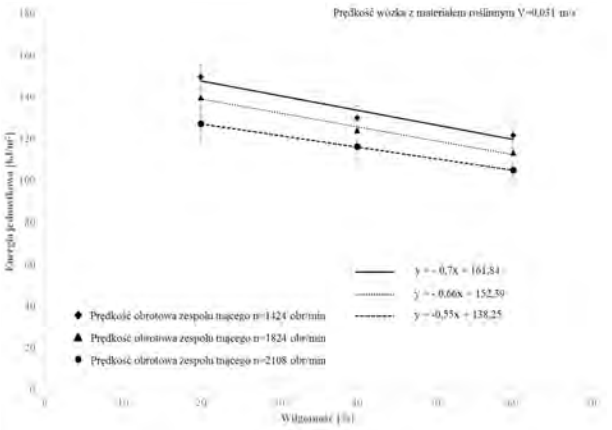


**Fig. 6.** Comparison of the course of unit cutting energy changes of Miscanthus giganteus as a function of 3 rotational speeds of the cutting assembly at the linear speed of the trolley carrying the plant material of V=0.031 m/s.

The unit cutting energy of Miscanthus giganteus as a function of moisture decreases for each of the tested rotational speeds of the cutting assembly (Fig. 6). The greater the rotational speed of the cutting assembly, the lower the unit cutting energy (Fig. 6). An increase in the rotational speed of the cutting assembly from 1424 rpm to 1824 rpm results in a decrease of the unit cutting energy by 14% on average and a change of the speed from 1824 rpm to 2108 rpm results in a further drop of the energy by 16 %, on average.

## CONCLUSIONS

1. The unit energy needed for cutting of the stems of Virginia Mallow grows as the moisture of the stem increases. This may be attributed to the morphology of the plant. In the cross-section of Virginia Mallow, fibrous tissue prevails.
2. An increase in the moisture of Miscanthus giganteus results in a reduction of the unit cutting energy for this plant. This may be attributed to a lower energy demand for squeezing of the moist plant. The stem of Miscanthus giganteus assumes a shape of a pipe as its cross-section diameter increases.
3. Because of the energy demand for the mere process of cutting, it is best to cut low moisture Virginia Mallow. Miscanthus giganteus is best cut when moist. These trends are independent of the linear and rotational speeds of the cutting assembly.
4. The unit energy of Virginia Mallow grows along with the rotational speed of the cutting assembly. In the cutting process of Miscanthus giganteus a reverse relation takes place, i.e. a drop in the unit cutting energy following the increase in the rotational speed of the cutting assembly. This phenomenon is attributed to different morphologies of the stems of these plants.

5. The most energetically advantageous operating parameters of the rotary cutting assembly for mowing of Virginia Mallow and Miscanthus giganteus are: rotational speed of the cutting assembly n=2108 rpm and its linear speed V=0.105 m/s. Harvesting of Virginia Mallow should be done when its moisture level is low while that of Miscanthus giganteus – when it is high.

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## BADANIE PROCESU CIĘCIA ROTACYJNEGO WYBRANYCH ROŚLIN ENERGETYCZNYCH

**Streszczenie.** W pracy omówiono wpływ wilgotności rośliny oraz prędkości liniowej i prędkości obrotowej noży rotacyjnego zespołu tnącego na energię jednostkową cięcia łodyg ślazowca pensylwańskiego i miskantusa olbrzymiego. Dokonano doboru najkorzystniejszych wartości parametrów roboczych rotacyjnego zespołu tnącego ze względu na minimalne zapotrzebowanie na energię w procesie cięcia badanych roślin.

**Słowa kluczowe:** ślazowiec pensylwański, miskantus olbrzymi, proces cięcia, rośliny energetyczne, energia jednostkowa cięcia, wilgotność, prędkość liniowa zespołu tnącego, prędkość obrotowa zespołu tnącego.

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# Energy Balance of a Prosument Microinverter On-Grid Photovoltaic System

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**Summary.** The paper presents investigations into the energy balance of a prosument photovoltaic system. The tests were performed on selected days from July through December 2013. The core element of the on-grid photovoltaic system was a WVD-260-230V/50Hz microinverter. The test stand allowed monitoring the parameters of the PV system operation. An effective monitoring was realized through the WVC modem software. In the energy balance, two types of PV modules were included: monocrystalline (AEMF130) and polycrystalline (CL130-12P).
**Key words:** photovoltaics, photovoltaic module, on-grid PV system, inverter, monitoring, energy balance, prosument.

## INTRODUCTION

Photovoltaics (hereinafter referred to as PV) is a new interdisciplinary field of science and technology comprehensively dealing with the process of direct solar energy conversion into electricity [5, 6, 10, 11, 12, 16, 18, 19]. Currently, in Europe, approximately 3 % of the generated energy comes from photovoltaics (the second RES after windfarms) [23]. PV systems are built from several components, depending on the type. The basic component of each PV system is a generator composed from a certain number of connected modules. It is estimated that in the total expenditure on the construction of a PV system, the cost of purchase of the modules amounts to approximately 45 % of the entire investment project [1, 17]. Fig. 1 presents data on the current world production of PV modules. Until 2012 Europe was a leader in the installed capacity of PV systems (approx. 70 $GW_p$ – where $W_p$ denotes the peak power determined under STC laboratory conditions). The total power of the PV systems installed worldwide as at the end of 2013 is estimated at 136.7 $GW_p$, approx. 37 $GW_p$ of which was installed last year and a majority of new installations is located in China and Japan (11.3 $GW_p$ and 6.9 $GW_p$ respectively) [23]. Last year, Europe tended to lag behind in terms of production of the PV systems (Fig. 1). It is predicted that in a few years Europe will account for less than half of the total worldwide installed capacity of PV systems.

The fundamental factor facilitating the advancement of photovoltaics are properly planned mechanisms of support. The ranking of attractiveness of selected PV markets by Ernst & Young allows for the macroeconomic, political, technological and legislative conditions. In the last ranking [1] covering 40 countries, Poland was on the 35$^{th}$ position (a year before – 2012 – Poland was the 26$^{th}$) while Germany was the 3$^{rd}$ (until last year it had held the 1$^{st}$ position). New legislation introduced in Poland known as 'small energy tri-pack' and new mechanisms of support, such as the PROSUMENT scheme [22], have not brought any significant changes in this matter. At the current legal status quo, there are no economic grounds for rapid advancement of photovoltaics due to insufficient mechanisms of government support that is currently directed towards energy policy based on coal.

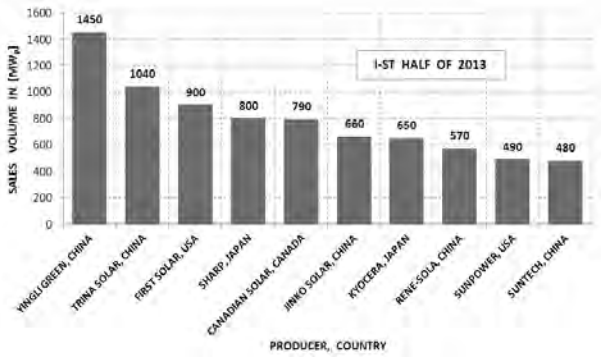


**Fig. 1.** The sales of PV modules in the first half of 2013 (own study based on data available from [22])

Quite different in this matter is the policy of Germany that introduced very attractive mechanisms of support for

photovoltaics. Photovoltaics in Germany is in the phase of a stable and predictable growth. It is possible that within five years it will start advancing without government subsidies.

## CONSTRUCTION OF THE TEST STAND

The investigations were conducted on a test stand whose diagram is shown in Fig. 2. It is an on-grid PV system built from two WVD-260-230V/50Hz microinverters adapted for continuous monitoring of their basic operating parameters. Individual elements of the PV system are stand-alone; hence, maintenance works do not disturb the operation of the other inverters. The monitoring system also allows deactivating the microinverter prior to physical disconnection of the MC4 connectors, which eliminates the risk of an intense arc occurring when connecting and disconnecting live wires in the DC circuit.

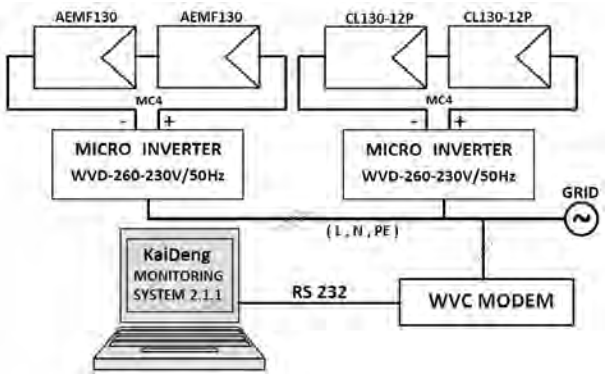


**Fig. 2.** Schematics of the test stand for the on-grid microinverter PV system

The main components of a PV system are two generators built from serially connected monocrystalline (AEMF130) and polycrystalline (CL130-12P) modules. Such a configuration results from earlier research of the author on an autonomous system of the inverter rated voltage of 12 V [14] and the necessity to adapt the parameters of the microinverter to the parameters of the PV modules of which the generators were built.

If we want to expand the PV system to a size beyond individual demand of the investor, a reverse power flow controller can be applied in the system [20] that will direct the surplus energy to power the heater in a domestic hot water (DHW) system.

Table 1 presents the basic parameters of the microinverter provided by the manufacturer.

**Table 1.** Basic technical parameters of the microinverter [20]

| Parameters | Values: |
|---|---|
| Models | WVD-260-230V/50Hz |
| Manufacturer | KAIDENG ENERGY |
| Recommended solar panels | 300 $W_p$ |
| DC MAX input current | 20 A |
| AC MAX output power | 260 W |
| DC MAX Open-circuit input-voltage | 50 V |
| DC input voltage range | 22 V ÷ 50 V |
| MAX output power factor | 0.99 |

Table 2 presents the basic parameters of the modules from which the PV generators were built. The analysis of the data has confirmed a correct range of output parameters of the PV generators, compared to the input parameters of the microinverter. As results from the data presented in table 2, the PV modules made in different technologies have identical nominal parameters, which also allowed a comparison of the efficiency of the monocrystalline and polycrystalline modules operating with the same type of microinverter under the same conditions. The monocrystalline modules are characterized by a higher nominal efficiency of individual PV cells but they use smaller working area. Visually, the monocrystalline modules have cells with a specifically cut edges, which results from the technology of their production.

**Table 2.** Basic parameters of the PV modules: AEMF130 and CL130-12P [21, 23]

| Parameters: | Values: | |
|---|---|---|
| | **AEMF130** | **CL130-12P** |
| Manufacturer | ACTIVE ENERGY | SOLTEC |
| Type of PV cells used | monocrystalline | polycrystalline |
| Maximum power $P_{MPP}$ | 130 $W_p$ | 130 $W_p$ |
| Maximum power voltage $U_{MPP}$ | 17.2 V | 17.2 V |
| Maximum power current $I_{MPP}$ | 7.56 A | 7.56 A |
| Open circuit voltage $U_{OC}$ | 21.6 V | 21.6 V |
| Short circuit current $I_{SC}$ | 8.02 A | 8.02 A |
| Dimensions | 1483x655x35 mm | 1483x655x35 mm |
| Weight | 12 kg | 12 kg |

During the measurement, the generators were set at the southern direction at the inclination angle of 35°. Such a setting, based on previous analyses of the author and other research [7, 8, 13] can be deemed optimum for this geographical location. The GPS position of the test stand was: 52.48°N and 19.67°E (vicinity of Płock).

The other elements of the PV system are: special PV wiring (cross-section of 4 mm²) fitted with MC4 connectors, special overcurrent protection on the DC and AC sides along with a B+C surge protection.

## METHODOLOGY AND SCOPE OF RESEARCH

The tests were performed on a complete low voltage on-grid PV system through two WVD-260-230V/50Hz microinverters. The microinverters have a special anti-islanding protection that disconnects it from the grid if blackout occurs. A reason for disconnecting from the grid may also be a case of a naturally sudden reduction in sun radiation [3, 4, 9, 12] to the level at which the output parameters of the PV generators are too low.

A component of a PV system that enables a continuous monitoring of its operation is the WVC modem. Its characteristic feature is that it does not require separate wiring to communicate with the inverters using the already existing one on the AC side.

Fig. 3 presents an example screenshot of a system monitoring the PV system. The only downside is the need of a permanent connection of the modem with the PC through a serial COM. The PV modules bearing numbers [04] 0008 and [04] 0075 presented in Fig. 3 in the application window [04] 0008 and [04] 0075 actually represent pairs of units of serially connected modules: AEMF130 and CL130-12P, respectively (Fig. 2). An additional advantage of this monitoring system is the possibility of separate supervision of individual components without interrupting the work of the other system elements. In this way, we can avoid many undesired phenomena that are likely to happen in systems built from serially connected PV modules (shading, malfunction of one of the modules, current or voltage incompatibility of the modules).

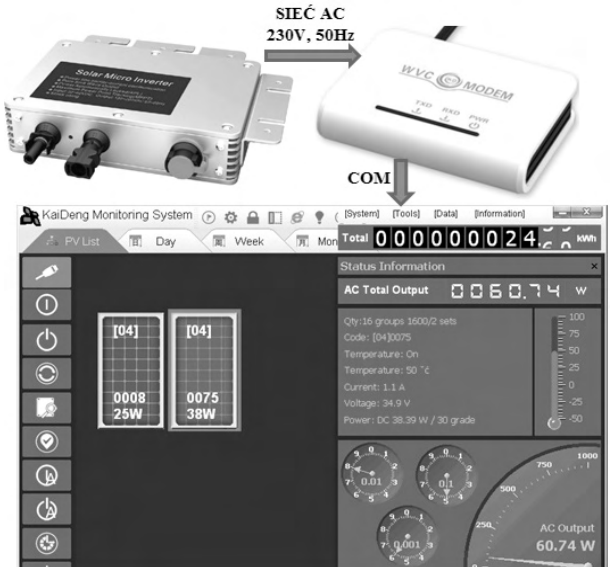


**Fig. 3.** Monitoring of an on-grid PV system (own study based on [20])

In the monitoring system built in this way, it is difficult to maintain the continuity of long-term measurements. Each application hang or an instantaneous blackout results in a system pause and it requires action of the operator to resume it. For this reason, the paper presents results of measurements for 7-day measurement intervals in each of the tested months. Fig. 4 shows an example screenshot of the monitoring application (KaiDeng Monitoring System 2.1.1.) Fig. 4 presents a recorded course of the subsystem operation for the AEMF130 monocrystalline modules in August 2013. The application allows an analysis of daily, weekly and monthly output parameters of the operation of individual PV generators and current temperature of individual inverters. Whether or not the continuity of monitoring is maintained, the total energy value generated by the PV system is also recorded.

The most difficult to record were the December data, when frequent outages of the microinverters operation occurred resulting from low insolation or presence of snow on the PV modules.

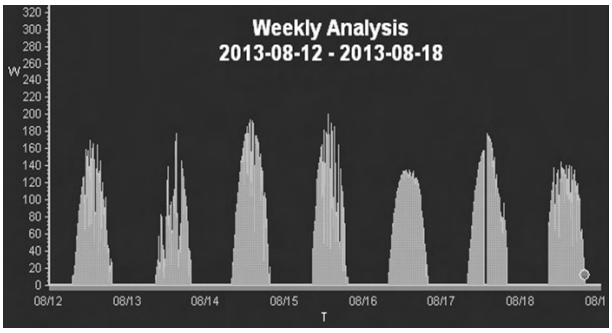


**Fig. 4.** Example screenshot of the WVC modem application

## RESULTS

Fig. 5 presents the energy balance of an on-grid PV system for the period from July through December 2013. The graphs show average daily values calculated based on a set of seven consecutive days in each month. The results for generators built from monocrystalline and polycrystalline modules have been distinguished.

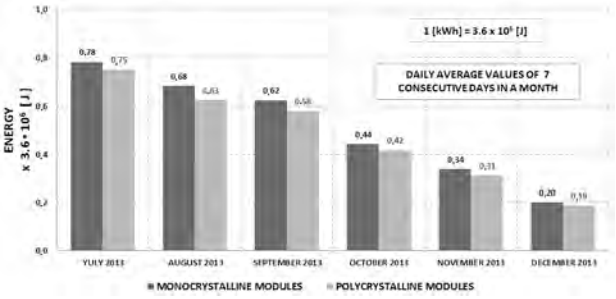


**Fig. 5.** Amount of AC output energy from the on-grid PV system

Numerous measurements [2, 17] have proven that PV systems built from modules based on crystalline silicon may generate a maximum of approx. 950 kWh per 1 $kW_p$ of installed capacity assuming an optimum direction and inclination of the PV generator. Analyzing the investigated system, we may estimate the yearly amount of generated energy in a PV system at 732 kWh for monocrystalline modules and 685 kWh for polycrystalline modules per 1 $kW_p$ of installed capacity of the PV generator.

## CONCLUSIONS

1. The application of microinverters for the construction of PV systems slightly increases the cost but allows the system to be easily extended and reduces the risk of possible malfunctions of the entire system.
2. In the conducted investigations, more energy was obtained from a PV generator built from monocrystalline silicon at identical power outputs of both generators.
3. The obtained measurement values of the generated energy are slightly lower than expected, which is most likely related to worse (in terms of photovoltaics) radiation structure in the second half of the year in our geographical area.

4. The application of monitoring systems allows recording operating parameters of the entire PV system without deactivating it for measurements. This also enables diagnosing malfunctioning system subcomponents and their quick renewal.
5. An additional advantage of photovoltaic systems built from microinverters is the possibility of independent monitoring of each PV module separately, which facilitates the identification of possible malfunctions.
6. The lack of vital economic mechanisms of support in Poland in the area of photovoltaics makes small prosument PV systems especially advantageous, and the energy from them could be used exclusively for the investor's needs.

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## BILANS ENERGETYCZNY PROSUMENCKIEGO MIKROINWERTEROWEGO SYSTEMU FOTOWOLTAICZNEGO DOŁĄCZONEGO DO SIECI

**Streszczenie.** W pracy przedstawiono badania bilansu energetycznego prosumenckiego sieciowego systemu fotowoltaicznego. Badania prowadzono w wybranych dniach od lipca do grudnia 2013 roku. Centralnym elementem sieciowego systemu PV był mikroinwerter WVD-260-230V/50Hz. Stanowisko badawcze umożliwiało monitorowanie parametrów funkcjonowania systemu PV. Efektywny monitoring prowadzono wykorzystując oprogramowanie dołączone do modemu WVC. W bilansie energetycznym uwzględniono dwa rodzaje modułów PV: monokrystaliczne – AEMF130 oraz polikrystaliczne – CL130-12P.
**Słowa kluczowe:** fotowoltaika, moduł fotowoltaiczny, sieciowy system PV, inwerter, monitoring, bilans energetyczny, prosument.

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# Photovoltaics – The Present and the Future

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**Summary.** The paper presents the possibilities of generation of electric energy with the use of solar cells operating on the basis of absorption of visible-range radiation and the photovoltaic effect. This study presents the advantages and disadvantages of photovoltaics and examples of the application of solar cells in industry and agriculture. Due to high investment costs, the development of photovoltaics is supported in many countries of the world through systems of subsidies or systems of fixed tariffs, which considerably enhances its attractiveness.
**Key words:** photovoltaics, solar radiation, BIPV.

## INTRODUCTION

One of the greatest challenges facing humanity is the replacement of shrinking resources of fossil fuels with renewable sources of energy while meeting the demand related with growing energy consumption all over the world. The solution to that problem is the development of an inexpensive method of utilisation of generally available sources of energy such as the Sun, water or wind, that nature has been using for millions of years. At present, the most dynamic development is noted in the case of solar energy. We can observe a considerable increase of interest manifested in the installation of solar panels and photovoltaic cells on the roofs of houses and in other places such as road signs or poster pillars. It is becoming more and more economically viable to build large installations, called solar farms, that provide electric power for large numbers of individual consumers. Special possibilities of application of that form of electric power acquisition are related to the so-called "small" power generation systems, especially those used in agriculture, where photovoltaics is utilised in such processes as agricultural produce drying, greenhouse production or storage of food products in cold-storage facilities.

There is an increasing tendency to implement programs supporting the growing utilisation of renewable energy sources. National governments place a strong emphasis on the diversification of energy sources, with the aim of reducing the exploitation of conventional resources and of lowering the levels of $CO_2$ emissions to the atmosphere. European countries more and more willingly revise their legislation to support the use of renewable energy sources, and the basis of energy policy till 2020 is the Program 3×20 which includes the following provisions:

- 20% reduction of greenhouse gas emission relative to the level of 1990,
- 20% reduction of energy consumption,
- 20% increase of the share of energy from renewable sources in the global EU energy production by the year 2020 [1].

## SOLAR RADIATION AS A SOURCE OF ENERGY

The Sun is the most powerful source of light reaching the Earth. It emits energy generated as a result of thermonuclear reactions taking place in the Sun. The radiation emitted by the Sun covers all the ranges of electromagnetic wavelengths. The greatest amount, i.e. 49% of energy from the spectrum of solar radiation, is emitted in the range of visible radiation (wavelengths of 380÷760 nm) [2]. Waves with lengths greater than 800 nm transmit 44% of solar energy, and 7% of that energy is emitted in the near-UV range (120÷300 nm). X-ray radiation and far-UV account for not more than 0.001% of the total energy. The Sun is also a source of radio-frequency waves (wavelengths above 1 mm). However, the energy of that radiation is negligibly small (of the order of $10^{-10}$ %) [3].

Photovoltaics makes use of that part of solar radiation spectrum which is generated in the photosphere, i.e. in the upper layer of the convective zone of the Sun. When solar radiation passes through the Earth atmosphere, the photons of solar radiation react with atoms, molecules, aerosols and

liquids contained in the atmosphere, on the pathway of two physical phenomena:

- absorption of radiation with the direction of wave propagation unchanged. The fundamental components of the atmosphere on which radiation absorption takes place include ozone ($O_3$), carbon dioxide ($CO_2$) and water vapour ($H_2O$). Ozone absorbs UV radiation, while carbon dioxide medium IR, and water vapour – wavelengths from the ranges of near and medium IR;
- scattering, i.e. change of the photon trajectory under the effect of contact with particles of dusts or aerosols contained in the atmosphere. Depending on the size of the scattering particles, the particular wavelengths are scattered in various ways.

Those two factors determine the atmospheric transmittance coefficient whose value is lower than 1. According to the Lambert-Beer Law, it leads to the reduction of radiation intensity proportionally to the path length through the atmosphere which is characterised by the value known as the air mass index (AM). AM is the parameter determining the optical path that has to be travelled by solar radiation passing through the atmosphere, normalised to the shortest possible pathway (when the Sun is in the zenith position). It is expressed by the following formula [4]:

$$AM = \frac{1}{\cos\theta}, \tag{1}$$

where:

$\theta$ – angle of deflection in the vertical plane (zenith angle).

The spectrum of solar radiation outside the atmosphere, denoted as AM0, is similar to black-body radiation spectrum at the temperature of 5743 K, and its total radiation intensity amounts to 1365 W/m². Whereas AM1 refers to the situation when $\theta = 0^{o}$, which means that the Sun is in the zenith (equatorial zone) and is equal to circa 0.7 AM0. In accordance with the adopted standards ASTM E 892, IEC 60904-3, unified for ease of results presentation, for the simulation of photovoltaic cells operation the coefficient of AM1.5 is used that relates to solar radiation in the situation when $\theta = 48.2^{o}$ and its intensity is 1000 W/m² [5]. Such conditions are used in the tests of photovoltaic cells aimed at the determination of their peak power, denoted on the modules as $W_p$.

Solar radiation is characterised by a variety of values, the most important of which are the following:

- **radiation flux** – radiation energy passing through a given surface in a unit of time (radiation power) $\Phi_e$ [W],
- **global radiation** $G$ or $E$ [W·m$^{-2}$] which is the sum of direct and scattered radiation, and sometimes also of radiation reflected from the surroundings. Global solar radiation is defined as the radiation intensity on a flat horizontal surface, incoming from the entire hemisphere of the sky,
- **irradiation** $H$ [kWh·m$^{-2}$], composed of the sum of direct irradiation (frequently called insolation), scattered and reflected irradiation, representing the energy received by a unit of surface area within a specified time,
- **insolation** $h$ [h] presented by means of average numbers of hours with directly observable operation of the Sun; occasionally it is referred to as e.g. the annual sum of insolation.

In the territory of Poland insolation varies within the range of 950 – 1250 kWh/m², while the mean time of operation of the Sun amounts to 1600 hours per year. Approximately 80% of the total annual sum of insolation is accounted for during the six months of the spring and summer season [4].

The energy of electromagnetic radiation from the Sun can be utilised in various processes of its conversion to other kinds of energy. Solar energy can be converted to the following kinds of energy:

- photothermal, when solar energy is converted to thermal energy (heat),
- photochemical, consisting in the binding of solar energy in chemical bonds,
- photovoltaic, utilising the photovoltaic effect during which electric energy is produced.

The most popular and widespread type of renewable energy generation is the photovoltaic conversion. The photovoltaic effect was first observed by Becquerel in 1839, in a circuit of two illuminated electrodes coated with AgCl or AgBr and immersed in an electrolyte. However, it was not until 1876 that Adams and Day succeeded in achieving that effect on a junction of Pt and Se, which permitted to conclude without a doubt that direct conversion of solar energy into electric power was possible [6]. The theoretical foundations of the photoelectric effect were developed on the basis of quantum mechanics in the years 1920-1930. Nevertheless, the strongest impact on the advancement of solar cells was the development, by Czochralski, of the method of obtaining silicon crystals of high purity [2].

## PRINCIPLE OF OPERATION OF PHOTOVOLTAIC CELLS

The first semiconductor cell based on a p-n junction was formed during the slow crystallisation of molten silicon and described by Russel Ohl in 1941. The research on its properties permitted the understanding of the role of p and n admixtures in controlling the properties of the semiconductor, and thus led to a revolution in microelectronics [6].

The principle of operation of all photovoltaic systems is based on the phenomenon of separation of charges on the junction of surfaces of two materials differing in the conductance mechanism. The fundamental structure of a solar cell is constituted by a strongly doped n-type area, i.e. the emitter, and a less strongly doped p-type base. During the exposure of such a semiconductor junction to light, the incident photons can generate an electron-hole pair of charges, which causes the generation of electromotive force on the junction. The generation of an electron-hole pair can take place only in the boundary layer of the junction. The carriers are separated, as within the area of the junction they are affected by electric field formed as a result of contact of two semiconductors with different conductance character. Due to that field, electrons and holes start moving in opposite directions resulting in their separation, the effect

of which is the formation of an external electric tension on the junction, i.e. the photovoltaic effect takes place (Fig. 1.). If a receiver is connected to the terminals of the junction, electric current will flow as long as photons keep falling on the cell. Only those photons participate in the generation of current carriers in the junction whose energy is greater than the semiconductor energy gap (or band gap) $E_g$, and in the case of silicon that condition is met by 30% of the spectrum range of solar radiation [3].

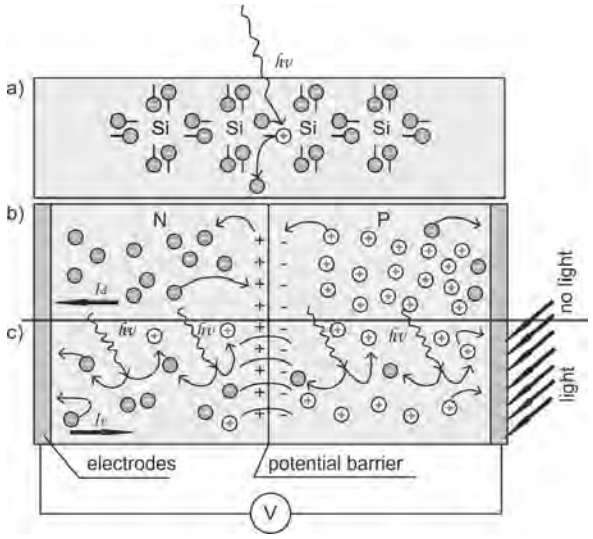


**Fig. 1.** Mechanism of photovoltaic effect: a) mechanism of generation of positive charge, b) flow of reverse diffusive current (no light), c) current flow (with light) [2]

The p-n junction based silicon cell is characterised by plotting the I-V curve, i.e. the graph presenting the intensity of output current of a photovoltaic generator as a function of voltage at a certain temperature and defined radiation intensity. The curve includes a number of points, presented in Fig. 2, which provide information on the basic parameters of the cell, as follows:

1. open circuit voltage ($U_{oc}$) – voltage on the terminals of an unloaded photovoltaic generator at a certain temperature and defined radiation intensity,
2. short circuit current ($I_{sc}$) – output current intensity under short circuit conditions at a certain temperature and defined radiation intensity,
3. $P_{max}$ – maximum power point and its coordinates: $U_{mpp}$ and $I_{mpp}$.

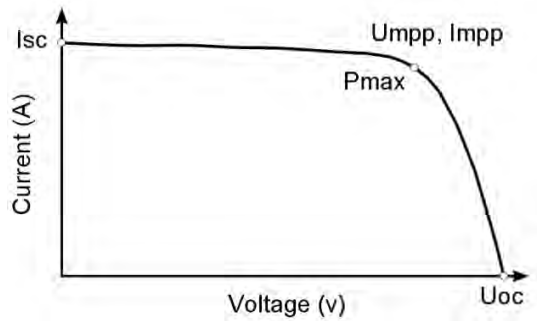


**Fig. 2.** Current-voltage curve of solar cell

The efficiency of photovoltaic conversion is defined as the ratio of output electric power to the total power of incident radiation [7]:

$$\eta = \frac{U_{oc} \cdot I_{sc} \cdot FF}{S \cdot A}, \tag{2}$$

where:
$U_{oc}$ – open circuit voltage [V],
$I_{sc}$ – value of short circuit current [A],
$S$ – cell surface area [m²],
$A$ – power of radiation falling onto the cell surface [W·m$^{-2}$],
$FF$– fill factor – parameter determining the performance of a photovoltaic cell [7]:

$$FF = \frac{U_{mpp} \cdot I_{mpp}}{U_{oc} \cdot I_{sc}} \cdot 100\%, \tag{3}$$

$I_{mpp}$ – value of current intensity at maximum power point [A],
$U_{mpp}$ – voltage at maximum power point [V].

The value of the fill factor is always lower than 1 and, like open circuit voltage, depends on the structure and type of the semiconductor layer, the level of doping of both areas of the p-n junction, and on the level of the inbuilt potential barrier and temperature of the junction. Very good cells are characterised by values of $FF > 0.8$ [8].

At present, the mass-produced solar cells have efficiency exceeding 20%. There is ongoing work on improving the efficiency of solar cells that would lower the costs of energy generation and result in shorter time of recovery of investment costs involved in the purchase of photovoltaic cells, and in increased competitiveness of such systems relative to other alternative sources of energy.

## KINDS OF PHOTOVOLTAIC CELLS

Currently, thanks to intensive development of research on photovoltaics, we can speak of four generations of solar cells. The first generation cells are based on silicon, the second most common element – after oxygen – on Earth. In nature it occurs primarily as a dioxide, being a component of e.g. quartz contained in the crust of the Earth. That compound is used to obtain, via chemical transformations, metallurgical silicon with 98% purity, that is next subjected to purification to obtain high-purity silicon.

Silicon monocrystals are obtained primarily with the method of Czochralski and with the method o zonal melting. Silicon blocks formed in that manner are cut into thin plates, with about 40% material losses. Next, using the method of diffusion, the p-n junction is formed in the silicon, an antireflection layer is applied, and metal (usually silver) electric terminals are inserted. In some cases surface texturing is applied to enhance the operation parameters of the cell.

Solar cells are also built using multi-crystal and poly-crystal silicon, with grain sizes from 1 mm to 1 cm and from 1 μm to 1 mm, respectively [6]. In that case silicon blocks are produced with the method of Bridgman or of block casting. However, the efficiency of such cells is lower than that of the single-crystal ones, and amounts to 14-15% [9].

For the needs of photovoltaics also silicon tapes and foil sheets are produced, permitting material losses during the cutting of large silicon blocks. The schematic diagram of a typical solar cell is presented in Fig. 3. It consists of a single p-n junction. The p-type silicon base is around 200 μm thick whereas the n-type emitter is around 100 μm thick. An antireflection coating layer is deposited over the emitter in order to minimise reflection losses. Metal contacts are placed at the bottom of the cell as a whole layer and at the top as fingers. Approaches for increasing the efficiency include making inverted pyramids at the surface, buried contacts, selective emitters and so forth. At present, c-Si solar cells have reached record efficiencies near 25%, for which the top and bottom surfaces have been well passivized. The theoretical values of efficiency for other silicon cells are as follows: for poly-crystalline silicon – 20,4%, for amorphous silicon – 10% [10].

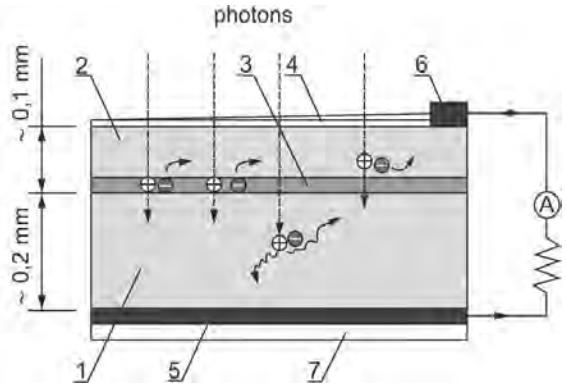


**Fig. 3.** Simplified schematic diagram of photovoltaic cell from crystalline silicon : 1 – p-type semiconductor, 2 – n-type semiconductor, 3 – boundary layer, 4 – antireflection coating, 5 – anode, 6 – cathode, 7 – base plate

Commercial cells of the first generation are characterised by efficiency in the range of 17-22%. Their production costs are high, mainly due to the relatively low level of automation of the production (many operations have to be performed by a qualified worker) and to the high cost of the necessary components. The current market share of cells of that type is about 63% [11].

The second generation cells are the thin-film. The reduced amounts of materials used in their production permitted a significant reduction of the production costs. The thin-film semiconductor structures are obtained primarily with the method of molecular beam epitaxy, liquid phase epitaxy and chemical vapour deposition. Their production requires the use of bases with high mechanical strength, e.g. low-quality silicon, glass, ceramic materials or graphite. The outer layer of the cell is usually textured to increase the active surface area. At present there are a number of kinds of thin-film cells on the market, utilising various materials like e.g. amorphous silicon, or multiple layers of amorphous and microcrystalline silicon, notably enhancing their efficiency.

Apart from the silicon cells, technologies are being developed that utilise such compounds as GaAs, CdTe, or the system of copper – indium – gallium – selenium (CIGS), with the highest efficiency achieved in laboratory conditions being 36.9% [10], and in the case of commercial cells 18.4% [11]. The high efficiency of those cells is mainly due to the fact that the range of absorption of radiation is shifted towards the visible radiation, which causes that the temperature effects, considerably reducing the operation parameters of cells, are lower and thus the cells can be used as covering of the facades of buildings. The application of new inorganic materials and cell production methods such as the screen process and spray pyrolysis notably reduced the costs of production and permitted the application of very thin layers on flexible base materials (metal, plastic, etc.).

The second generation cells are now more and more popularised by their manufacturers. This is related with the possibility of their wholly automated production and lower price of the components used than is the case with the first generation cells. As a result of this their market share is constantly growing.

The third generation cells include photoelectrochemical cells among which we can distinguish organic cells, polymer cells and dye-sensitised solar cells (DSSC). In those structures the photovoltaic effect does not take place in the traditional sense. The functions of the semiconductor in the conventional solar cells are separated, and other organic materials are used for the absorption of radiation. Thanks to their simple structure and cheap components, they are perceived as an opportunity for rapid development of widely available technology of production of solar cells. The main obstacle for their popularisation is their low efficiency, oscillating at the level of several percent in the case of commercial applications. Their present market share does not exceed the level of a fraction of a percent, and the most popular ones are the polymer cells of the "power plastic" type produced by Konarka. The phenomenon of those cells consists in the fact that the alternating single and double bonds occurring in polymers cause that they behave like a semiconductor. A slight modification of the structure of the polymer chain may lead to the creation of materials with such properties as those of rubber or linoleum, which in the case of the production of solar cells permits to impart to them any shape required, and to modify their colour [12].

In recent years we have witnessed the slow development of the fourth generation of solar cells, comprising the latest achievements of research. Those include, among other things, structures making increasingly frequent use of the methods of nanotechnology, such as e.g. quantum dot cells which appear as a substitute of the sensitising agent (dye) in DSSC. That group includes also the so-called plasmon cells, in the case of which on the surface of the semiconductor layers of surface plasmons are applied, bound with nanoparticles, that cause an amplification of light absorption, reduce internal recombination effects, and notably improve the parameters of the cells [13].

## PHOTOVOLTAICS SYSTEMS

In practice electric power is generated with the use of both individual cells and complex systems with power ratings of up to tens of MW. Large solar power plants, built of thousands of single photovoltaic cells, can be encountered

all over the world, and the biggest of those, the target power rating of which is to be 500 MW, is currently being built in the USA. In Poland the largest installation of this type, with power rating of 1 MW, is situated in the locality of Wierzchosławice (Małopolskie Province).

Next to the large solar power plants, a notable group of producers of renewable energy are individual consumers who install photovoltaic cells in their households, on the roofs of buildings. Photovoltaic cells can also be found in many portable devices, e.g. portable refrigerators, garden lamps, road signs power supply systems, phone chargers, mechanical toys, as well as supplementary energy supply systems in cars, airplanes or yachts.

Photovoltaic systems currently in use can be classified in the following groups:

- consumer-use electronic equipment,
- stand-alone systems (off-grid),
- systems connected to the grid,
- hybrid systems (operating in conjunction with other power generation systems),
- special purpose devices.

Large photovoltaic systems are most often connected to the grid. In such a case they require the use of additional equipment such as inverters, as the cells produce direct current. The function of the inverters is not only to convert direct current to alternating current, but also to maintain at correct levels the parameters characterising the quality of electric power (voltage, frequency, time profile, supply continuity) in conformance with the European standard PN-EN 50160:1998. Such systems are most frequently connected to the grid, which solves the problem of energy transport over long distances.

In the case of stand-alone systems, apart from inverters it is also necessary to foresee some energy storage systems. At present those are most often arrays of batteries, the quality of which largely determines the efficiency of the whole power generation system. Apart from storage batteries it is also possible to use systems converting electric power into other useful forms of energy, e.g. heat pumps which – supplied by solar cells – can generate heat for house heating or for heating water.

In agriculture it is possible to utilise hybrid systems combining the production of heat and electric power (systems composed of photovoltaic cells and an air or liquid heat converter). In such a case solar radiation falling on the surface of the photovoltaic cell is transformed into electric energy, and the heat generated in the course of the process, a negative phenomenon in solar cells, is taken off by air flowing above the cell or by a liquid flowing beneath it, depending on the type of the device structure. During the absorption of the heat the photovoltaic cell is cooled, and thus its efficiency is improved [14]. Systems of this type can be used e.g. during the drying of agricultural produce, for drying of biomass for the production of fuels or for the heating and lighting of greenhouses [15]. The schematic diagram of such a device is shown in Fig. 4.

Stand-alone systems are also used in agriculture for such functions as e.g. the supply of electric fences on pastures or of systems pumping water to reservoirs for the irrigation of crop cultures or for farm animals.

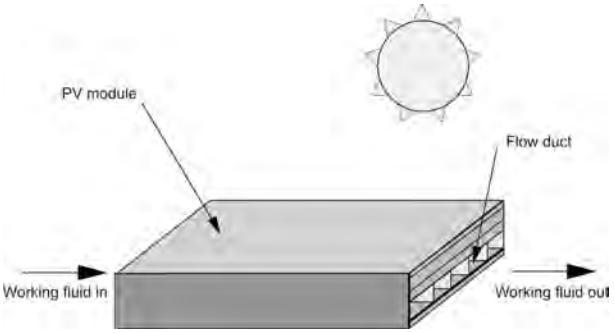


**Fig. 4.** Schematic diagram of a photovoltaic–thermal collector with water heating

Apart from systems generating electric power alone, photovoltaic cells can also be encountered in co-generation and tri-generation systems, in which heat and refrigeration are produced in conjunction. Such systems can be used successfully in the food industry that utilises large amounts of all of those kinds of energy.

## BUILDING INTEGRATED PHOTOVOLTAICS

Attempts have been undertaken at integrating photovoltaic systems with buildings (BIPV – building integrated photovoltaics). In its concept, BIPV strives to create the maximum of possibilities of utilisation of the surface area of a building for the production of electric power. A typical example is the covering of the south-facing facades of buildings with photovoltaic panels. In such an application, the panels replace conventional facade materials, which reduces the cost of the facades as such, and thus also the total investment cost. Until recently the main problem facing such a solution was the visual effect, as facades covered with photovoltaic panels were simply ugly. However, now the market offers both coloured and flexible-based photovoltaic panels, so their application depends only on the imagination and vision of the architect, and additionally makes the building appearance more modern and environment-friendly. BIPV systems can be either stand-alone ones or grid-connected, and their primary advantage is that they make the building cheaper to maintain as the photovoltaic panels generate power at the peak-load times, permitting the limitation or substitution of using the most expensive power provided by the power supply grid. That requires careful analysis and selection of tariffs offered by the power supply operators.

Other advantages of BIPV systems include the following:

- Integration of the photovoltaic modules into the building envelope in a so-called “non-ventilated facade”, both on public buildings such as office complexes, production buildings, shopping centres or schools, and on private buildings such as indoor gardens or terraced houses. The modules replace traditional building materials (e.g. spandrel glass) in a new structure and create an ambient inside temperature all-year round,
- “Ventilated facades” can be installed on existing buildings, giving old buildings a whole new look. These modules are mounted on the facade of the building, over the

existing structure, which can increase the appeal of the building and its resale value [16],
- Possibility of incorporation of solar modules into saw-tooth designs and awnings on a building facade. The angle of the awning increases access to direct sunlight, meaning increased energy. These can be used in entrances, terraces or simply as awnings to shade the rooms inside, protection from wind and rain. They also protect against lightning, being an electrical resistor,
- Usage of photovoltaics in a building envelope replaces traditional building materials and building processes. For example using BIPV in roofing systems may replace batten and seam metal roofing, and traditional 3-tab asphalt shingles,
- The glass-glass modules can be utilised as balustrades on balconies, for example for large rented accommodation or terraced houses, creating an eye-catching structure [17],
- Usage of solar modules as thermal insulation through the sandwich-construction of the modules themselves, the layer of air within the modules and the ray absorption by the crystalline silicon and thin film solar cells. This means that less energy is wasted by heat loss from the interior, reducing heating costs and keeping the building at an ambient temperature,
- Repelling of unwanted noise pollution and creation of a screen against potential electromagnetic interference, including so-called electro-smog. This makes them particularly useful in situations with large amounts of sensitive electrical activity, for example hospitals or airports [18].

Obviously, in the process of designing buildings with integrated photovoltaic systems one should comply with the same requirements that must be met by standard photovoltaic systems, concerning the exposure to sunlight and shading of the panels, and taking into account the position of the Sun relative to the panels during the year. At the current state of knowledge, BIPV appears to be one of best concepts for the acquisition of electric power from renewable sources, that should be implemented and actively developed in the future. This method of exposing the use of photovoltaics may have an effect on increasing the ecological awareness of the population and enhancing the level of acceptance for that form of power generation. With this method we can utilise all available and suitable surfaces of the walls and roofs of not only houses and apartment blocks, but also of industrial buildings or buildings devoted to farming and food production, making them more ecological and at the same time less dependent on the conventional suppliers of electric power.

## SUPPORT SYSTEMS FOR PHOTOVOLTAICS

In Poland the development of photovoltaics is a very slow process mainly to the lack of suitable legislation that would provide detailed regulations concerning the conditions for connecting such systems to the power grid, or for the take-off and sale of energy produced in such systems. In other EU countries such regulations have been functioning for years, in conjunction with various support mechanisms aimed at increasing the level of utilisation of renewable energy sources. The best solution, applied e.g. in Germany and Japan, was the introduction of so-called Feed-in-tariff (FIT), i.e. state subsidies to each kWh of "clean" energy. Those subsidies proved to be the most effective mechanism of supporting the development of photovoltaics, and are now the foundation determining stable development of energy markets all over the world. Apart from FIT, other systems of support used in the world include tax incentives (Lithuania, Slovakia), guaranteed subsidies in the form of environmental payments, or investment subsidies that one can apply for prior to or in the course of realization of a project [19]. The only support system currently functioning in Poland is the system of so-called green certificates. For several years now there have been announcements of new legislation on renewable energy sources that is to replace the existing system. In the case of agricultural and food production there is also the possibility of taking advantage of EU subsidies for the development of agriculture, amounting even up to 75% of costs related with investments concerning the production of "clean" energy, available via the Agriculture Restructuring and Modernisation Agency [20].

## CONCLUSIONS

Technologies utilising solar radiation for the production of electric energy have been in use for over 30 years. At present it is one of the fastest developing alternative methods of acquisition of electric power. Compared to conventional power generation plants, the use of photovoltaic systems has numerous advantages, such as:
- power source – the Sun (practically inexhaustible energy resources),
- no significant effect on climate change of generation of pollutants, e.g. exhaust fumes and gases,
- low operation costs of such installations,
- no moving parts (longer service life of systems),
- possibility of safe operation at high temperatures,
- high reliability of cells/panels (up to ca. 20 years of service life),
- fast assembly of installations,
- possibility of installations on existing structures,
- possibility of installation at almost every location and providing power supply for objects situated in inaccessible areas or in areas with poorly developed electric supply grid,
- high level of social acceptance,
- low failure rate.

The disadvantages of photovoltaic systems are the following:
- high cost of complete PV installations,
- sensitivity weather changes limiting the production of electric power,
- lack of an economically effective system of energy storage (the current generation batteries have not achieved a sufficient level of development in terms of service life and storage capacity).

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## FOTOWOLTAIKA – TERAŹNIEJSZOŚĆ I PRZYSZŁOŚĆ

**Streszczenie.** W niniejszej pracy przedstawiono możliwości wytwarzania energii elektryczne za pomocą ogniw słonecznych, których działanie opiera się na absorpcji promieniowania widzialnego i efekcie fotowoltaicznym. Omówione zostały zalety i wady fotowoltaiki oraz przykłady zastosowania ogniw słonecznych w przemyśle i rolnictwie. Ze względu na wysokie koszty inwestycji rozwój fotowoltaiki wspiera się w wielu krajach świata poprzez systemy dopłat lub taryf stałych, co znacznie zwiększa jej atrakcyjność.

**Słowa kluczowe:** fotowoltaika, promieniowanie słoneczne, BIPV.

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# Laboratory Tests of Force Sensor Applied in Agricultural Mechatronic Equipment

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**Summary.** The present article presents the results obtained from the test of a bolt with magnetoelastic sensor applied in agricultural mechatronic devices. This element is used in the electrohydraulic lift system applied in agricultural tractors in order to enable the measurement of tractor – agricultural machine system interaction force. The scope of works encompassed the measurements of the sensor output voltage vs. pressure force applied to the bolt with magnetoelastic sensor incorporated inside. Aforesaid tests have been performed for diversified bolt positioning towards applied force and for various values of the sensor power supply voltage.
**Key words:** laboratory tests, mechatronics, agricultural tractor, force sensor, force measurement, bolt, magnetoelastic sensor.

## INTRODUCTION

Mechatronics is a discipline of science combining the concepts associated with the following fields: mechanical, electronic, IT engineering as well as signals control and transmission. The scope of mechatronics encompasses the devices, circuits and electromechanical systems incorporating sensors and actuators collaborating with signals processing system and with communication system. One of most important features of mechatronic devices consists in true representation of information in the form of electric signals and high automation level. The vehicles steering systems are the principal area for mechatronic devices application. The role of sensors converting the non-electric values(force, moment of force, rotation angle, movements etc.) into an electric signal (current, voltage, frequency, phase displacement etc.) is important in the operation of this type of systems.

Nowadays, the number of sensors installed in motor vehicles as well as in agricultural machines is significant. Many new designs and solutions are created in order to meet inter alia the following requirements [6, 7, 12, 13]: high accuracy, high sensitivity, durability, reliability, small dimensions, no impact of outside conditions on their operation. In order to ensure their correct operation in difficult conditions, the sensors must be provided with proper signal processing and forming signals [1]. The signal quality will be ensured by means of amplifying systems, A/D and D/A converters selected individually for specified sensor. Therefore the digital communication buses [3, 5, 14] are used in contemporary motor vehicles and agricultural vehicles for information transmission from sensors and communication between individual mechatronic devices. The signals in such systems are transmitted via proper buses using standard conductors or fibre optic cables [15, 19] to increase the system reliability and to provide the possibility of a quick and reliable diagnosis by means of "the best" available method [8, 17, 18] in case of damages.

The latest mechatronic solutions are used in contemporary tractors and agricultural machines in the scope of work management for majority of control circuits as well as for working elements functions. The purpose of various types of sensors is to provide precise information on current operation parameters for an element, circuit or system to enable their correct functioning.

## BOLT WITH MAGNETOELASTIC SENSOR

Due to various types of automatic control systems applied in agricultural tractors e.g. for tool position towards the tractor and their interaction force, it is necessary to use adequate set of sensors for data acquisition and analysis. The magnetoelastic sensor incorporated in the bolt in order to supply information about interaction force between the tractor and attached tool is one of the basic sensors coupling the both elements of the tractor – machine system. The efforts intended to increase the effectiveness and work efficiency of the assemblies are continued since many years [2, 9, 10, 16].

KMB 060 magnetoelastic sensor with nominal force value of ±60 kN and overload capacity ±160 kN [20], man-

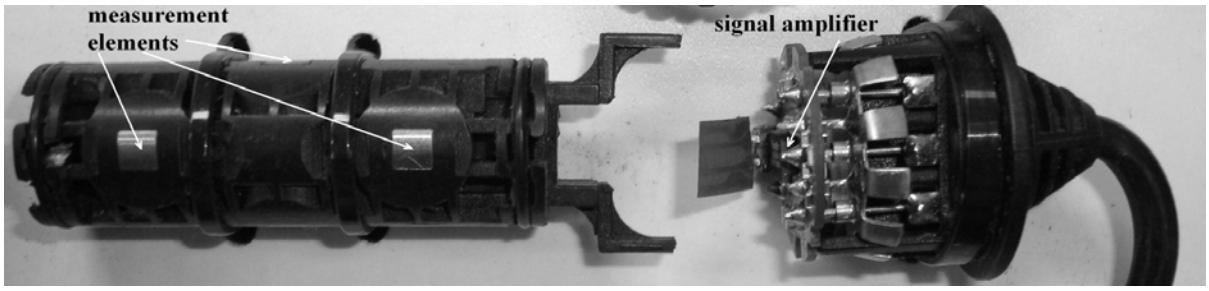


**Fig. 1.** Magnetoelastic sensor

ufactured by Rexroth Bosch Group and illustrated in Figure 1 has been used for tests. The sensor represents a group of parametric sensors operation in accordance with principle of electric signal variation vs. measured value [11]. Such sensors are used in electrohydraulic lifts system of agricultural tractors, where it is required to determine the traction force.

The magnetoelastic sensors are based on the phenomenon of permeability variations in ferromagnetic in case of their deformation within elastic strains. Electromagnetic forces induced in measuring elements are insignificant, in order of magnitude equal to mV. Therefore the magnifying systems are applied in order to enable the measuring signal reading.

## LABORATORY TESTS

The tests were completed on a laboratory station [4] prepared in the framework of a master thesis; its measuring system is illustrated in Figure 2. Research works consisted in changes of force applied to the bolt caused by the increasing of oil pressure in manual hydraulic pump with piston diameter of 33 mm.

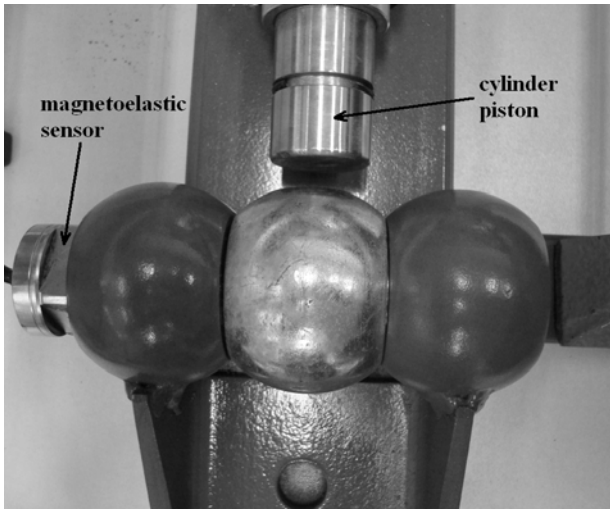


**Fig. 2.** Laboratory measuring system

In order to determine the curve representing the sensor output voltage vs. force applied to the bolt U=f(F), the measured value of pressure (by means of pressure gauge) applied to the bolt with magnetoelastic sensor incorporated inside was converted into force value, in accordance with the following equation:

$$F = p \cdot S, \tag{1}$$

where:

$F$ – force applied to the bolt with magnetoelastic sensor incorporated inside,

$p$ – pressure applied to the bolt with magnetoelastic sensor,

$S$ – surface area of actuator piston cross-section.

The value of sensor output voltage vs. force applied to the bolt was measured by means of an universal meter. The measurements were carried out for various setting angles of the bolt (Fig. 3) and various values of power supply voltage of the magnetoelastic sensor (Fig. 4).

In order to obtain the negative value of force applied to the bolt, the latter was reversed by angle of 180°.

## CONCLUSIONS

From the tests it appears that the obtained characteristics of magnetoelastic sensor is linear. The value of output voltage depends on the angle of bolt setting as well as on power supply voltage of the sensor.

From the analysis of sensor positioning angle towards applied force (Fig. 3) it appears that the sensor operation is correct up to the angle value of 45° only. The error is the greatest in case of limit measured values of force impact of ± 22 kN. In case of the bolt positioned perpendicularly to applied force (angle of 90°), the sensor becomes inoperative (only the value of idle voltage is present). Therefore, the working direction of magnetoelastic sensor must be polarized. Each change working angle may result in an incorrect force measurement.

From the analysis of the impact of sensor power supply voltage on its operation (Fig. 4) it appears that the sensor operation is correct in the scope of voltage values specified by the manufacturer (8-12 V). In case of voltage value lower than 11 V the shape of sensor curve becomes more flat.

The tests presented herein demonstrated the impact of basic operation parameters of magnetoelastic sensor on its operation characteristics. The measurements repeatability contributing to the correct operation of the whole tractor – machine system is extremely important from the measurement point of view due to its location in the agricultural tractor and heavy duty working conditions.

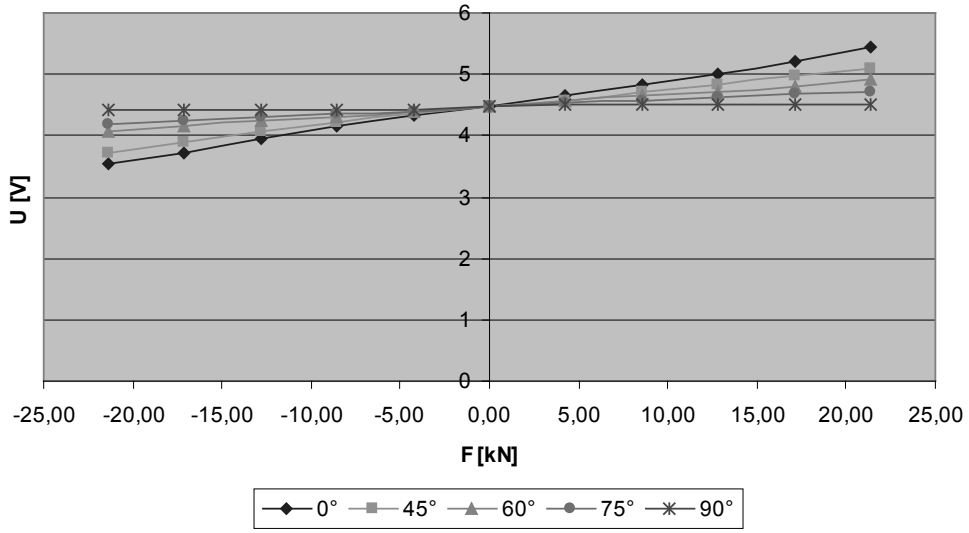


**Fig. 3.** Magnetoelastic sensor output voltage vs. force applied to the bolt depending on the bolt setting angle.

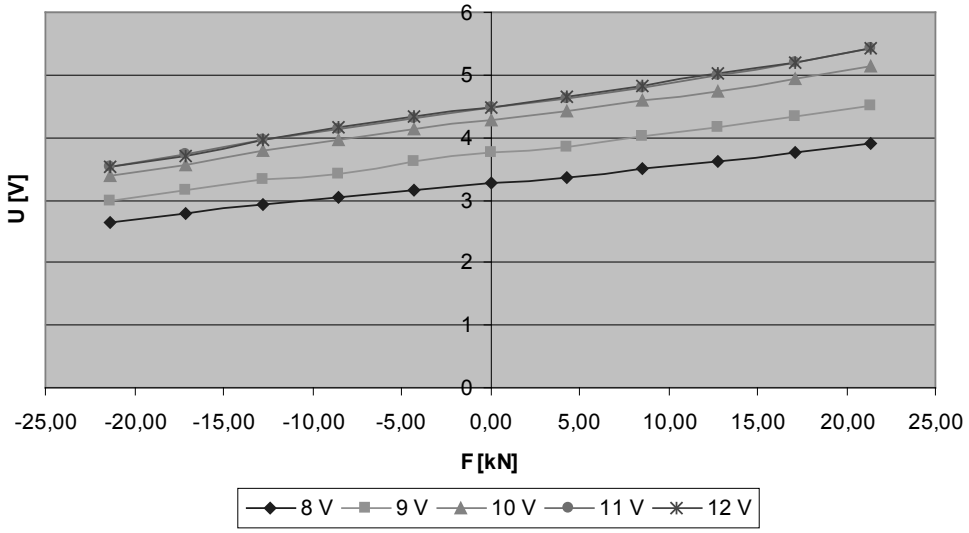


**Fig. 4.** Magnetoelastic sensor output voltage vs. force applied to the bolt depending on power supply voltage of the sensor

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## BADANIA LABORATORYJNE CZUJNIKA SIŁY STOSOWANEGO W ROLNICZYCH URZĄDZENIACH MECHATRONICNZYCH

**Streszczenie.** W artykule zaprezentowano wyniki badań sworznia z czujnikiem magnetosprężystym jako elementu stosowanego w rolniczych urządzeniach mechatronicznych. Element ten stosowany jest w układzie elektrohydraulicznego podnośnika ciągników rolniczych. Jego rolą jest pomiar siły wzajemnego oddziaływania układu ciągnik-agregat.
W ramach prac wykonano pomiary wartości napięcia wyjściowego czujnika, w zależności od wartości siły nacisku wywieranego na sworzeń z umieszczonym wewnątrz czujnikiem magnetosprężystym. Badania te wykonano dla różnego ustawienia sworznia względem działającej siły oraz dla różnych wartości napięcia zasilającego czujnik.
**Słowa kluczowe:** badania laboratoryjne, mechatronika, ciągnik rolniczy, czujnik siły, pomiar siły, sworzeń, czujnik magnetosprężysty.

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# The Evolution of "Media Oriented Systems Transport" Protocol

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**Summary.** The communication protocols applied in vehicles have gone through long lasting development. Their initial purpose was to support the communication functions in systems supporting conventional point – to – point connections and simultaneously to control the motor operation with regard to emissions. They have made it possible to test vehicle subassemblies in central diagnostic mode. The throughput of communication network required for the solutions in the scope of vehicle control and diagnostics are limited (≤ 10 Mpbs). They are unsuitable for smooth multimedia transmission from several sources.

The article contains consistent summary of Media Oriented Systems Transport (MOST) communication protocol features. MOST bus underwent three principal development phases. In its present specification it comes close to the standard enabling easy transmission of digital data in the widely applied Ethernet networks format. The text contains also the consideration of diagnostic testers makingit possible to eliminate the defects of MOST bus.

**Key words:** MOST, Vehicle Information Network.

## INTRODUCTION

The first multimedia installation based on MOST bus and protocol was introduced in the year 2001. In the same year, MOST bus was applied in the next ten vehicle models. In the year 2013, MOST Cooperation consortium could report MOST introduction into 140 vehicle models including new models i.e. Audi A3 and Mercedes class S. MOST bus and protocol have been present in popular medium segment vehicles e.g. Volkswagen Golf and Opel Insignia as well as the models: Rolls Royce Ghost, Phantom and Wraith.

The functioning of majority of wire communication buses in motor vehicles is based on linear bus topology [4, 12, 21, 28, 29]. Therefore MOST bus is a unique solution because it is based on ring topology (Fig. 1). The application of fibre optic solution is another specific feature. The communication via cable connections is possible after transceivers replacement. One of devices (master) contains the complete database for devices in the ring (Fig. 1b).

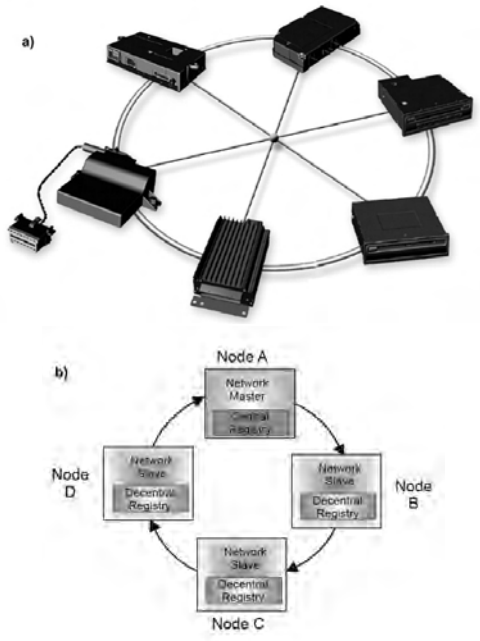


**Fig. 1.** The communication bus in ring topology: a) view of real devices, b) communication mechanism diagram [19, 21]

MOST bus operation is typical for ring topology. The data block received from preceding node is used as information and commands source. The block received from preceding node is regenerated and forwarded. Turned off devices transmit optical signal without its analysis. The data transfer is finished when the block is received by its sender. The ring contains some special nodes responsible for the ring management i.e. commands generation on the basis of user activity and for the ring synchronization (Fig. 1b). MOST protocol and bus are dedicated to multi-

media networks which are sometimes called Infotainment networks [1, 4, 5, 7, 26]. High throughput levels are required for data stream in such networks. Despite MOST150 standard functioning since several years, this fact has been not mentioned in many publications. Most often the graphical presentations inform about the throughput of about 25 Mbps (Fig. 2) which is underestimated by three times. The throughput of 150 Mbps will be probably exceeded soon. The manufacturers of Plastic Optical Fibers (POF) indicate the throughputs of 500 Mbps along the section of 20 m or 170 Mbps along the section of 115 m [3, 6]. The transceiving equipment is prepared for operation with throughput of 5 Gbps [2, 13]. The current throughput is sufficient to use MOST as an element in the network supporting images received from security camera or from the games network [5, 18, 25].

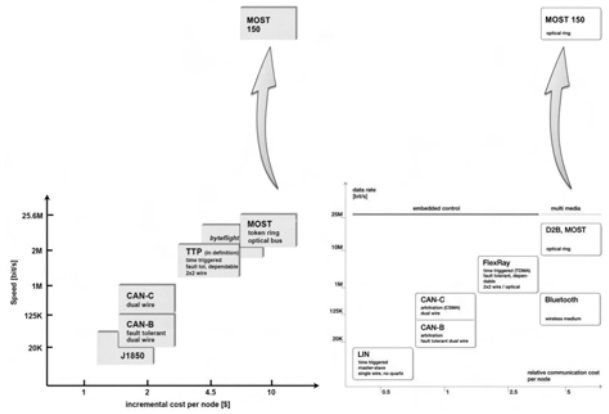


**Fig. 2.** Lack of information on the throughput of MOST 150 bus in data summaries for communication protocols [19, 27]

The communications based on Function Blocks is the common feature of all MOST versions. Because MOST is a "new" communication method, it is possible to find references for its individual elements in layer type ISO-OSI model. Application layer commands are the key MOST Function Blocks as the standardized commands used to control the behaviour of devices installed in the ring and enabling the data transfer. It is assumed that each device installed in the ring and conforming with MOST specification will support the Function Block commands. Built-in support for Function Block is necessary in order to manage such devices. The functional addresses are assigned to the devices after their introduction into the ring. By means of said addresses the devices performing the role of controllers can read and declare the operation parameters of the devices performing the role of saves. The devices and accessible software can be divided into three (3) groups: Human Machine Interface – the software making it possible for the user to communicate with MOST bus devices, program user's interface; Controllers – the devices functioning as the controllers for other devices (change of sound intensity, change of GPS system map on the screen), they manage the information about the Function Block commands for controlled systems; Slaves – the actuators which do not contain any information about the system structure but respond to the Function Block commands associated with them. Due to their passive role in the system, the slave devices can be added to and removed from the system without changing the configuration of the whole bus. The communication method based on Function Blocks is common for all versions of MOST protocol: 25, 50 and 150.

## MOST25

The numbers contained in the MOST protocol version refer to approximated maximum communication speed expressed in Mb $s^{-1}$. Detailed data are contained in the Table 1.

The frame is the basic communication unit in the second layer of ISO-OSI communication model. In MOST25 the data are transformed in the form of blocks consisting of 16 frames. Each of 16 frames contains a part of message controlling the nodes. The control message is subdivided into the group of frames in order to reduce the utility data loading with control data.

The utility data within a single frame occur in the form of stream data (e.g. sound) transferred in synchronous mode and in the form of package data (e.g. GPS system). The length of parts of frame associated with synchronous and asynchronous may vary. This length is preliminary determined by means of boundary descriptor. Therefore it is possible that package section does not exist or its length is equal to 9 four – bit words (Fig. 3). The initial bits of the preamble are used for slave nodes time synchronization. Two bits of control data are the part of larger message controlling the network and subdivided into frames in the whole block. The purpose of parity bit is to increase the transmission security [8, 23].

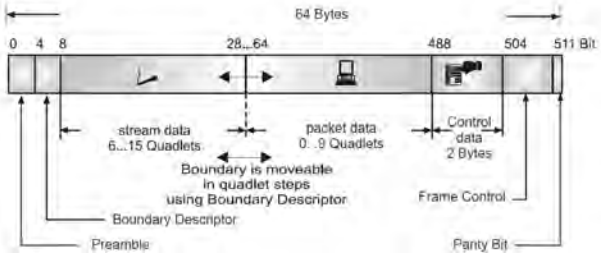


**Fig. 3.** MOST25 protocol frame [8, 9]

## MOST50

As can be seen from the name of protocol in MOST50 version, its communication speed should be two times higher than in case of MOST25. Except of increased speed of transceivers, the length and structure of the frame have been changed in physical layer. MOST50 frame is two times longer than in case of MOST25 and contains 128 bytes. MOST25 contains 4 bytes of control data arranged in two locations of the frame (Fig. 3). MOST50 contains 11 control bytes located in the header only on the beginning of the frame (Fig. 4).

It should be emphasized that the frame structure is more simple and more flexible in MOST50 version (control data

located in one header area). In case of lack of stream or package data it is possible to remove the area dedicated for such types of data.

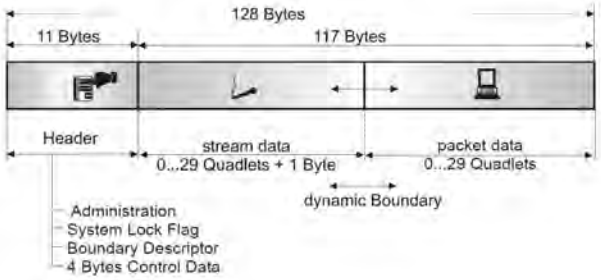


**Fig. 4.** MOST50 protocol frame [8, 9]

## MOST150

In case of the transmission in the framework of MOST150 protocol, it is required to increase the transceivers speed three times in comparison with MOST50 version. The frame is also three times longer and equals to 384 bytes. Its internal structure is not changed. The length of stream and package part can be adjusted in this part of data. The protocol is more efficient that in the case of version 50 because the area to be used for data has been increased from 117 to 372 bytes and accompanying control part has been increased from 11 to 12 bytes only [9, 23].

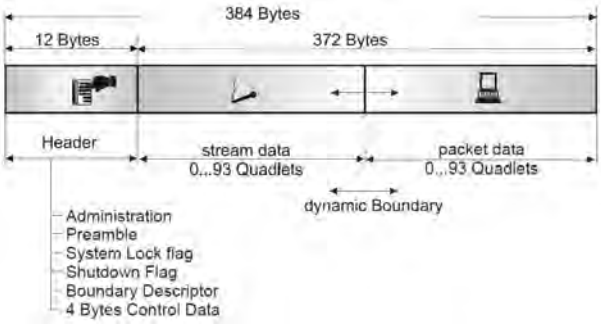


**Fig. 5.** MOST150 protocol frame [9]

From the structures of MOST25, 50 and 150 frames illustrated in Figures 3-5 it appears that there are no key changes introduced in MOST150. The previous synchronous communication and the support of new data called isochronous is actually possible in the stream communication part. An example for isochronous data is the data with sampling frequency different than basic frequency of the bus operation. The synchronous mode is simulated regardless of asynchronous data transfer. There are three types of isochronous channel support: Audio/Video packages streaming, discrete frames streaming and QoS (Quality of Service) isochronous mode.

Audio/Video packages streaming in isochronous mode consists in asynchronous data packages transfer depending on bus loading and on task load of MOST150 interface package support. Therefore the video support application is not required to provide band reservation or to establish the connection any more.

The discrete frames streaming is used when data sampling (e.g. audio) is other than bus speed. In such case audio data are transferred by the bus with sampling data in order to make it possible for the receiving node to transmit the data with sampling speed conforming with streaming speed.

QoS (Quality of Service) isochronous mode makes it possible to transmit the streaming data with specified quality. In typical situation, an available band is shared by the applications. The quality assurance consists in reservation of required throughput for specified application [9, 23].

The asynchronous channel is often called package and Ethernet channel sharing the band with the synchronous channel. This channel makes it possible to send 93 four-bit words in a frame. MAMAC (MOST Asynchronous Medium Access Control) layer is responsible for TCP/IP protocol transmission via asynchronous channel in MOST25 and MOST50 versions. MOST150 contains MHP (MOST High Protocol) layer. Actually it is possible to address in asynchronous channel by means of 16-bit package addresses (conventional MOST addressing) and 48-bit Ethernet addresses (addressing by means of MAC addresses) [9, 23].

**Table 1.** Bandwidth of MOST 25, 50 and 150 frame [9]

| Parameter | MOST25 | MOST50 | MOST150 |
|---|---|---|---|
| Streaming data | | | |
| Minimum bandwidth [Mbps] | 8.48 | 0.38 | 0 |
| Maximum bandwidth [Mbps] | 21.17 | 44.93 | 142.85 |
| Packet data | | | |
| Minimum bandwidth [Mbps] | 0 | 0 | 0 |
| Maximum bandwidth [Mbps] | 10.84 | 44.54 | 142.85 |
| Control data | | | |
| Minimum bandwidth [kbps] | 405.84 | 448.00 | 512.00 |
| Maximum bandwidth [kbps] | 405.84 | 810.62 | 1130.00 |

## DIAGNOSTIC TOOLS

High throughput of MOST bus combined with fault tolerance is possible as a result of fibre optic transmission medium. The fibre optic communication makes the diagnostics and bus faults elimination more difficult [22]. However it is possible to gather information from typical diagnostic testers communicating with motor vehicle via standard OBD connection. It is impossible to establish any connection with the bus ring by means of typical multimeters. The transmitting – receiving diodes and bus socket are shown in Fig. 6.

The diagnostic workshops are unable to perform the repairs by means of actually possessed measuring and testing equipment. There are two methods used to detect a failure in fibre optic ring circuit. The first method is based on error message generated by master module in the bus. The master module contains the database for bus elements configuration. On the basis of times of response to the test signal introduced from the module into fibre optic conductor, the master module is able to determine, with high probability, the defective module or the fibre optic section with problematic communication. In order to verify the diagnosis it is necessary to carry out the tests by means of special testers.

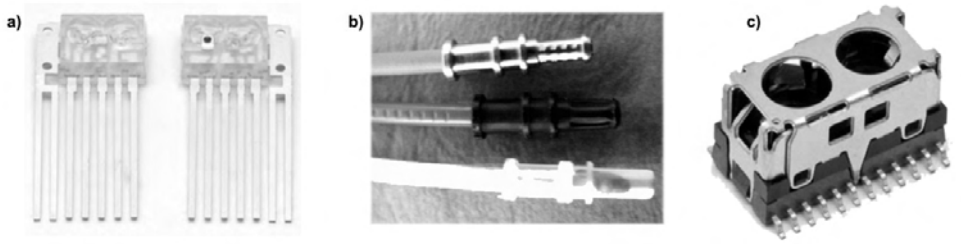


**Fig. 6.** Elements of fibre optic ring of MOST bus: a) transmitting – receiving diodes; b) fibre optic cables plugs; c) socket of MOST node [2, 8, 9, 10, 13]

The tests consist in the replacement of defective module by the tester and in checking whether the ring is closed in this manner. Another method consists in fibre optic conductor continuity check performed by means of two testers, i.e. one tester used as the source of optical signal and another as the receiver thereof. Except stream travel continuity it also possible to measure light stream attenuation. An example of such tester for D2D bus is illustrated in Fig. 7. Fig. 7b illustrates how to connect two testers in order to check the fibre optic section.

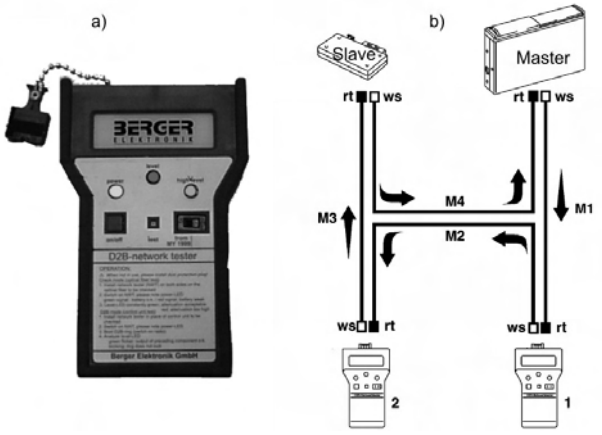


**Fig. 7.** Diagnostics of optic ring on the example of D2B bus: a) tester; b) connection method [14]

The examples of motor vehicles with multimedia system based on MOST bus are the new models of BMW vehicles. The diagnostic system for such vehicle consists of a measuring head and software running on personal computer. The measuring head is connected with an Ethernet interface on one end and to OBD diagnostics socket of the vehicle on another end. Therefore it is possible to gather standard information about vehicle condition or to reprogram the modules. Since several years the optical interface connector enabling direct tester connection to the optical ring is the mandatory equipment of such tester. Fig. 8 contains two photos of such devices – GT1 measuring head and OPS DiCAN MOST tester. Thanks to comprehensive testers functions and accompanying software it is possible to read the error codes, to cancel the codes to carry out programming, data decoding, to locate the components and to display the connection diagrams.

Although the testers systems described above are sufficient for fails detection and elimination in workshops, their capabilities are rather limited in case of preparation of the new solutions of MOST bus. In case of nonstandard problems or in case of necessity to determine the technical boundaries of the project, it is necessary to use laboratory equipment dedicated to MOST protocol. Such specialized solutions are available for research tasks, e.g. „MOST150 Controller 6161" measuring card manufactured by GOEPEL electronic (Fig. 9a). Using this card it is possible to perform typical bus tests i.e. ring continuity check and to configure MOST bus systems collaborating with CAN or LIN networks. Ready to use sets of tests are available for elements checking for their compliance with MOST protocol requirements. An example of dialog window of such software delivered by LeCroy is illustrated in Fig. 9b [11, 24]. The physical tests are carried out by means of oscilloscopes supplied by the same company. Similar solutions are proposed by Agilent. Its N6466A MOST Compliance

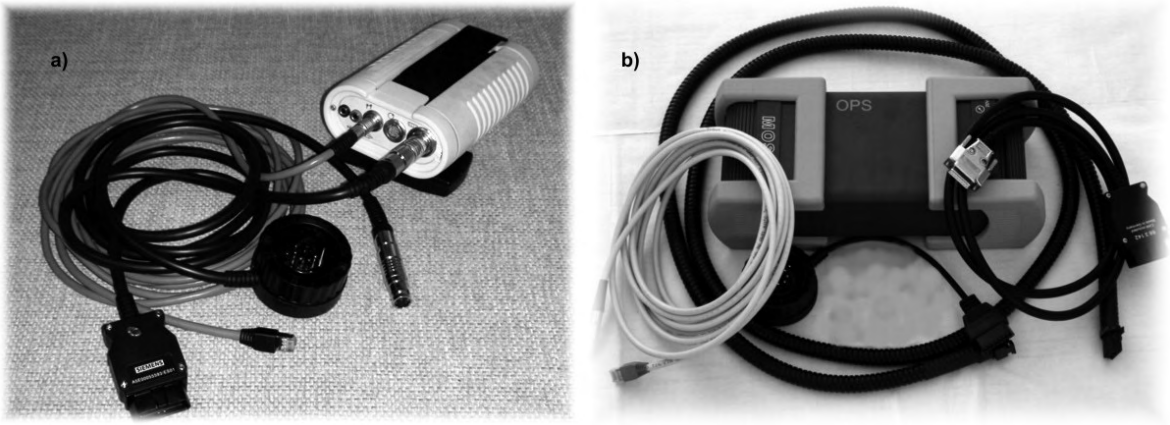


**Fig. 8.** Testers heads dedicated for BMW vehicles: a) GT1; b) OPS [16, 20]

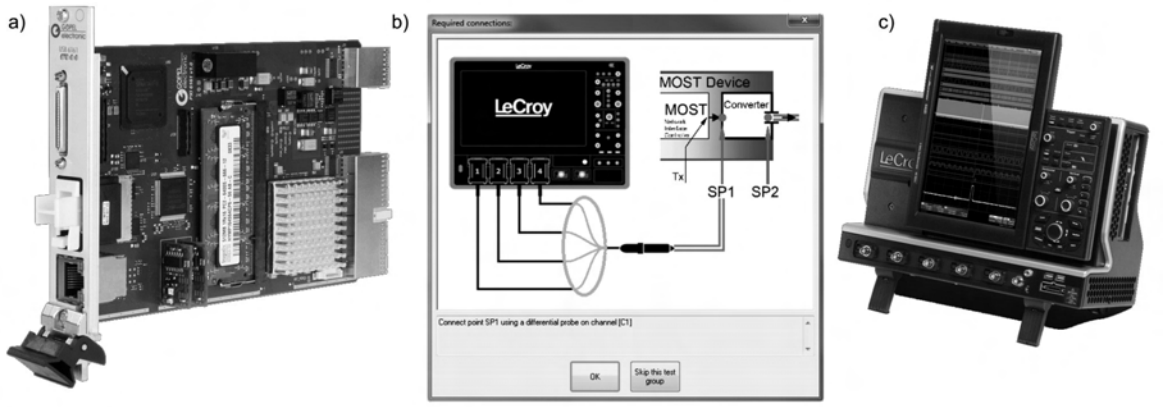


**Fig. 9.** Advanced tools for analysis of MOST protocol MOST bus devices: a) measuring card; b) LeCroy testing package; c) oscilloscope for LeCroy package [24]

Application running on Infiniium oscilloscopes makes it possible to verify the compliance of hardware layer with requirements established by MOST standard.

## CONCLUSIONS

The multimedia systems installed in vehicles have come a long way from the first lamp type receivers used in the thirties of the 20th century. The first fibre optic multimedia bus Domestic Digital Bus designed in early nineties of 20th century was the initial phase of MOST bus. The evolution of protocol used in Media Oriented Systems Transport bus makes it possible to make the following conclusions:

- at the moment, the MOST bus is the fastest multimedia bus dedicated to motor vehicles;
- MOST protocol in MOST150 version is characterized by high flexibility in the scope of band allocation for synchronous and asynchronous data;
- MOST150 version is characterized by facilitated transmission of data based on IP protocol and by introduced Quality of Service support;
- MOST bus makes it necessary to use specialized diagnostic tools for elimination of errors in fibre optic ring;
- there are automated tools available for verification process automation for devices compliance with MOST standard;
- there is such a rich variety of currently available elements, devices and descriptions that the special databases are created to contain the information about MOST bus elements [17].

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## EWOLUCJA PROTOKOŁU „MEDIA ORIENTED SYSTEMS TRANSPORT”

**Streszczenie.** Protokoły komunikacyjne stosowane w pojazdach przeszły długą drogę rozwoju. Początkowo miały tylko obsługiwać komunikację w systemach zastępujących tradycyjne połączenia typu punkt-punkt. Jednocześnie kontrolowały pracę silnika pod kątem emisji zanieczyszczeń. Pozwalały i pozwalają na centralną diagnostykę podzespołów samochodowych. Rozwiązania sterowania podzespołami pojazdu oraz diagnostyki wymagają niewielkich przepustowości sieci komunikacyjnej (≤ 10 Mpbs). Nie nadają się do płynnego przesyłania multimediów z kilku źródeł.
Artykuł zawiera spójne zestawienie cech protokołu komunikacyjnego Media Oriented Systems Transport (MOST). Magistrala MOST przeszła trzy główne etapy rozwoju. W aktualnej specyfikacji zbliża się do standardu pozwalającego na łatwe przesyłanie danych cyfrowych w postaci zgodnej ze szeroko stosowaną w sieci Ethernet. W tekście zamieszczono także rozważania na temat testerów diagnostycznych pozwalających na usuwanie usterek magistrali MOST.
**Słowa kluczowe:** MOST, Vehicle Information Network.

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# A Study of a Heat Pump Ground Collector

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**Summary.** The paper presents selected issues related to the investigations into a ground collector of a heat pump fitted in a low energy single-family house. The experimental investigations performed in a test station (a single family house fitted with space heating) should allow an estimation of the influence of selected operating parameters of the ground collector on the performance of a heat pump.
**Key words:** ground source heat pump, vertical collector, spiral compressor, ground heat source, coefficient of performance (COP).

## INTRODUCTION

The increasingly expanding range of applications of heat pumps depends not only on their advanced design and functionalities but also on the workmanship and the efficiency of the ground heat source. In many countries, the heat pump market is dominated by the brine/water type [18, 22]. The trend is beginning to change in favor of the air/water heat pumps, despite the fact that ground heat pumps are characterized by high coefficients of performance and reliability. The said potential is conditional upon proper workmanship of the ground heat source. Poorly built installations spoil the opinion of not only the geothermal systems but also the entire heat pump technology.

From the analysis of available data on heat pumps, out of all installed heat pumps the prevailing are ground source heat pumps that, due to a rather cold climate, are the preferred solution in Poland. In Poland, in the ground source heat pump sector, the most frequently applied are pumps fitted with vertical (60%) and horizontal (30%) collectors. As results from the data [8, 18], there are two reasons for the prevailing status of vertical collectors (practically twice the number of horizontal collectors). Firstly, there exists a general conviction that systems fitted with vertical collectors have better performance and reliability and, secondly, systems fitted with horizontal collectors have terrain-related limitations (a plot size of approx. 4 times the area of the heated building is required for proper operation of horizontal collectors).

Energy-related analyses along with the analyses of the efficiency of pumps fitted with ground source collectors (both vertical and horizontal) have already been performed in many scientific centers [17]. Hepbasli et al. [5] have determined the energy effects for a system in which the compressor pump operated with vertical collectors. Following this analysis, thermal efficiency of the ground source collector ducts was determined along with the coefficient of performance. Akpinar and Hepbasli [1] have analyzed energy-related problems and expenses for heat pumps (fitted with vertical collectors) used for heating purposes. The authors have developed a simulation model that can be used for the analysis of expenses when a heat pump is applied for heating purposes. Kurpaska et al. [13] in his experimental research have determined the efficiency of a heat pump fitted with vertical collectors used for the heating of a glasshouse. In the work by Kurpaska et al. [12], a theoretical analysis was performed of the change of the thermal capacity of a ground source collector depending on the ground humidity and temperature. As can be observed, the efficiency of a heat pump depends on a variety of design, configuration and climate related factors. Hence, the purpose of this paper is to analyze the efficiency of a heat pump fitted with vertical collectors.

## CHARACTERISTICS OF THE RESEARCH OBJECT

### CHARACTERISTICS OF THE RESEARCH OBJECT

A heating system utilizing the brine/water heat pump was installed in a two story single-family house of the total usable area of 156 m². Low temperature space heating was applied in the ground and first floors. The water in the heat-

ing circuits on the ground and first floors was fed by two separate distributors powered with two separately controlled circulation pumps, which allowed an easy control of the thermal load of the heat pump.

From the analysis of the available literature it results that the demand for heat, for new buildings with good quality thermal insulation, is 40-50 W $m^{-2}$ [8]. Assuming a unit thermal load of 50 W $m^{-2}$ and the usable area of the building of 156 $m^2$, an approximate thermal load of the building of 7.8 kW was obtained. If the same heat pump is used for the production of domestic hot water then, for a 4 person family, an additional 1 kW needs to be added [30]. Eventually, for a house of the area of 156 $m^2$ a heat pump of the capacity of 9 kW was applied.

## COMPONENTS OF THE HEAT PUMP

The heat pumps used in low energy homes are controlled with thermostatic expansion valves. The realization of the adopted scope of experimental research forced the application of a heat pump controlled with an electronic expansion valve. Purchasing serially manufactured heat pumps was not an option. Instead, components made by reputable manufacturers from the refrigeration industry were used for its construction

R407C was used as refrigerant and plate heat exchangers by WTK were used in the condenser and evaporator circuits

The applied R407C refrigerant is a three-component mixture. Each of these components has a different evaporation temperature. In order to ensure 100% evaporation of each of the components, a super-heater of drawn-in gas was used. This eliminates the fluid uptake into the compressor and improves the coefficient of performance of the thermodynamic cycle.

The plate heat exchangers were selected through Avogadro2 rev. 2.0. software. The standard working parameters for a brine heat pump are B0/W35, which denotes the refrigerant evaporation temperature (0 °C) and the condensation temperature (35 °C). Assuming an expected difference in the glycol circuit amounting to ΔTgs=3 °C and 5 °C for superheating and subcooling of the refrigerant, a P7 series 30-plate heat exchanger was selected [27]. Fig. 1 presents a diagram of the applied heating system.

## SELECTION OF THE GROUND SOURCE

The efficiency of a heat pump increases as the difference between the ground heat source and air heat source decreases. The most effective ground heat source is ground water, whose temperature, irrespective of the season, remains on a constant level of approx. 10 °C. This is also a cost effective solution if the depth to ground water does not exceed 7 m and the wells (in a dual well system) are drilled no deeper than 15 m.

The simplest and the cheapest ground heat source solution is the air drawn to the heat pump, however the application of air as an external heat source in our climate is ineffective. In the winter, when the temperatures outside are below zero, the performance of such a system decreases to the value of COP=2-3 along with its heating capacity, which may render the space insufficiently heated [10, 14].

There are also vertical or horizontal collectors (flat or spiral). The latter are cheaper but cover a large area of the plot – two to four times greater than the usable area of the house.

Due to limited plot development possibilities and bad soil conditions (sand was found at the depth of 1-2 m) the construction of a ground heat source in the form of a horizontal collector was given up. Due to high additional costs of the determination of the ground thermal capacity, the examination of the heat transfer capacity by geothermal probes was also given up.

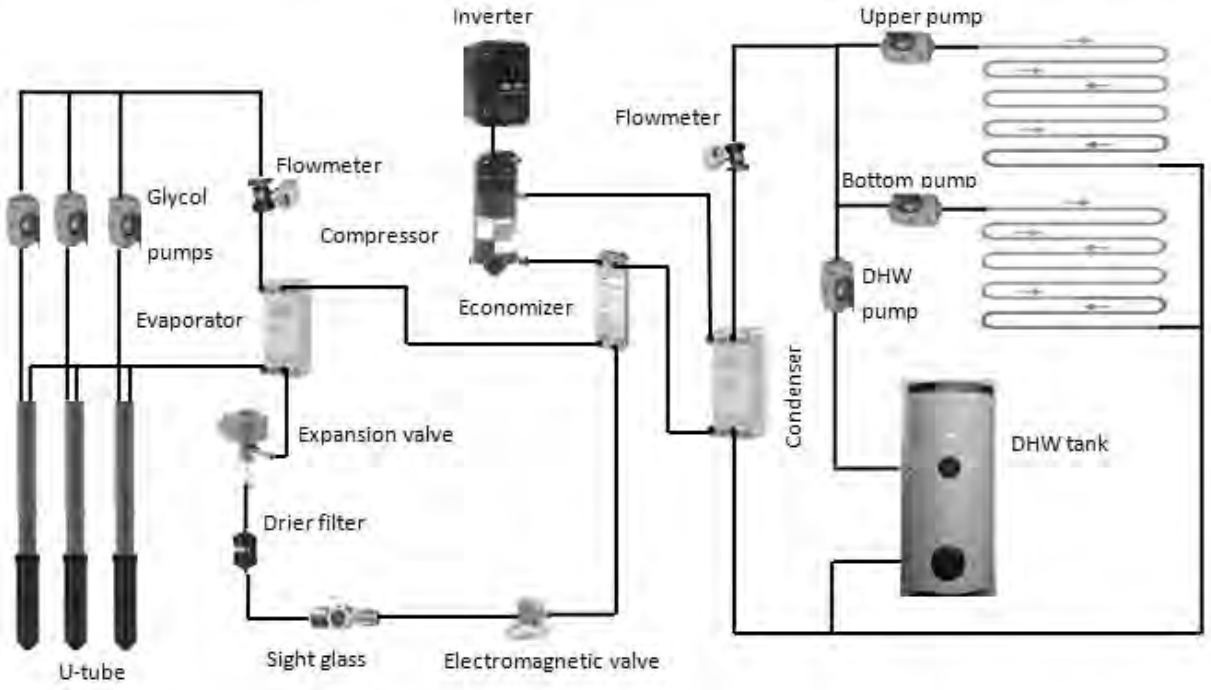


**Fig. 1.** Diagram of the heating system utilizing a heat pump

Dedicated Energeo software (dedicated by Aspol, a supplier of the vertical collector probes) was used for the selection of the vertical collector. Upon entering of the parameters of the heat pump to the Energeo software for the assumed coefficient of ground heat capacity of 38 W $m^{-1}$, a total required length of the vertical collector of 186 m was obtained using U probes filled with 20% solution of ethylene glycol. Three probes were used, 62 m each connected to a wall distributor located in the boiler room, hydraulically balanced with ball valves.

## THE TESTING PROCEDURE

The heat pump was used in the space heating in constant cycles:

– Cycle 1 working-time 60 minutes, dwell time 60 minutes,
– Cycle 2 working-time 120 minutes, dwell time 60 minutes

During the tests, basic operating parameters, needed for the determination of the energy balance were recorded.

The application of two-speed circulation pumps in individual circuits of the ground source and space heating allowed an easy adjustment of the mass flow of water and volumetric flow of brine. The application for an electronic expansion valve in the freon circuit allowed investigating the heat pump for the refrigerant evaporation temperatures in the range from -5 °C to 2.5 °C.

The tests of the vertical collectors were performed for the space heating mode on and production of domestic hot water. For the assumed constant refrigerant evaporation temperatures a series of tests were carried out for varied demand for heat.

In the space heating circuit the tests were performed for the following cases:

– Space heating on the ground floor only,
– Space heating on the ground and first floors simultaneously.

For the determination of the heating capacity of the condenser a standard relation was applied:

$$Q_{con} = C_{p,w}\, M_w \left(T_{w,out} - T_{w,in}\right), \tag{1}$$

where:
$Q_{con}$ denotes the heat at the outlet from the condenser, $M_w$ denotes the mass flow of water. The cooling capacity of the evaporator was calculated analogically.

The coefficient of performance of the heat pump at a moment in time (t) was determined from a standard relation:

$$COP_{HP} = \frac{Q_{con}(t)}{W_{com}(t)}. \tag{2}$$

A change in the thermal load (change in the mass flow of water, change in the capacity of the receiver) forces a change in the refrigerant and water condensation temperatures in the heating circuit downstream of the condenser, which is why for individual measurement cycles (τ) the average value of the coefficient of performance (COP) was determined according to relation (3)

$$COP = \frac{\int_0^\tau Q_{con}(t)dt}{\int_0^\tau W_{com}(t)dt}. \tag{3}$$

## RESULTS OF EXPERIMENTS AND DISCUSSION

The preliminary research was conducted in the 2012/2013 heating season. During the research, basic operating parameters, needed for the determination of the heat pump energy balance were recorded.

Designations on the figures:

– Tgs, out– temperature of glycol at the inlet to the evaporator,
– Tgs, int – temperature of glycol at the outlet from the evaporator,
– Tsh,out – temperature of return water from the heating circuit,
– Tsh,in – temperature of water fed to the heating circuit,
– Tfl – floor temperature on the ground floor,
– Tev – refrigerant evaporation temperature.

The volumetric flow of glycol in the ground circuit obtained during the experimental research was 1.92 m3 $h^{-1}$ (speed 1) and 2.30 m3 $h^{-1}$ (speed 2) for a simultaneous operation of all three loops of the ground source.

In the heating circuit, the mass flow of water was 0.09 kg $s^{-1}$ (speed I) and 0.13 kg $s^{-1}$ (speed 2) for the circuit pump activated on the ground floor and 0.16 and 0.22 kg $s^{-1}$ for a simultaneous operation of the pumps on the ground and first floors.

COP and the heating capacity were determined for each measurement cycle. To asses the measurement uncertainty for all experiments, a method recommended by Moffat was applied [20]. The calculated measurement error was ±2.45% and ±3.15% respectively.

Fig. 2 presents the trend in the changes of the temperature of brine for the space heating operating on the ground and first floors. During the operation of a heat pump the temperature of the brine, as recorded at the inlet to and outlet from the evaporator, drops gradually. When heat is collected from the ground by the vertical collectors the ground temperature around these collectors decreases.

For the refrigerant evaporation temperature 0 °C an average ΔTgs=2.6 °C was observed along with a drop in the glycol temperature at the inlet to the evaporator (42%) and the outlet from the evaporator (56%) in a 60 minute measurement cycle. For the refrigerant evaporation temperature –2.5 °C a ΔTgs=2.9 °C was observed along with a drop in the temperature of 45% at the inlet and 60% at the outlet.

During the first measurement cycle, for the assumed constant refrigerant evaporation temperature of 0 °C the efficiency in the heat transfer in the evaporator drops, which is a result of a reduction of the temperature difference between the glycol and the freon circuits. As a result, a higher brine temperature can be observed at the outlet from the evaporator. The temperature of the brine at the inlet to the evaporator remains constant.

Fig. 3 presents the influence of the change in the volumetric flow of glycol in the ground source circuit on the

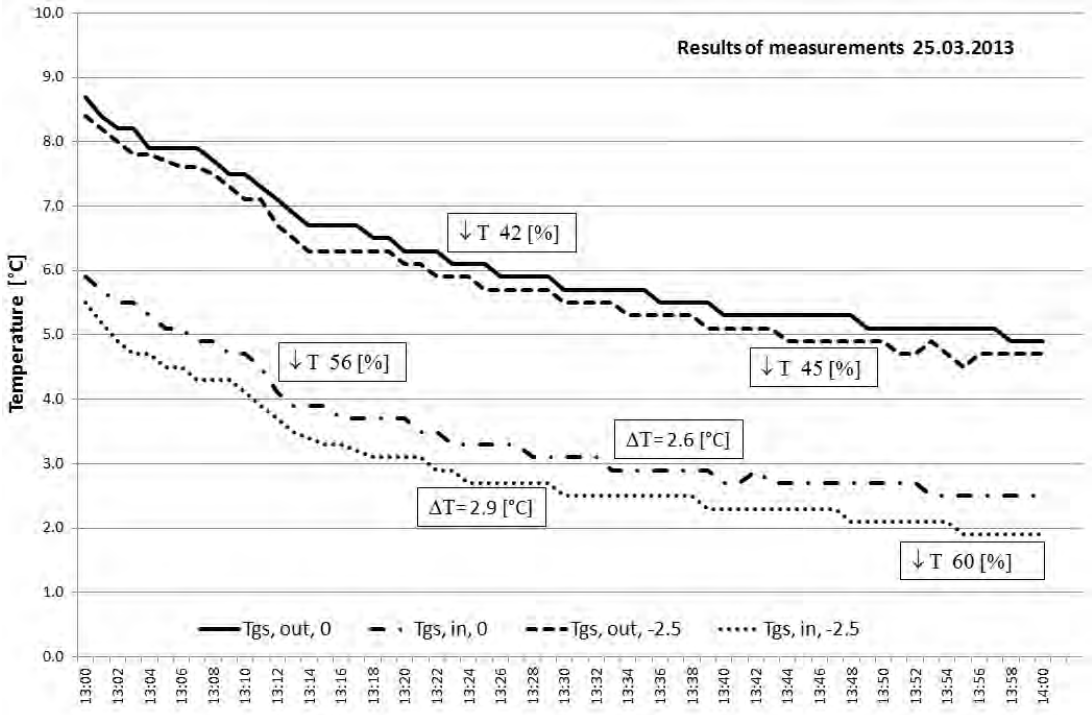


**Fig. 2.** Changes in temperature in the ground source circuit for the refrigerant evaporation temperature of -2.5°C and 0°C

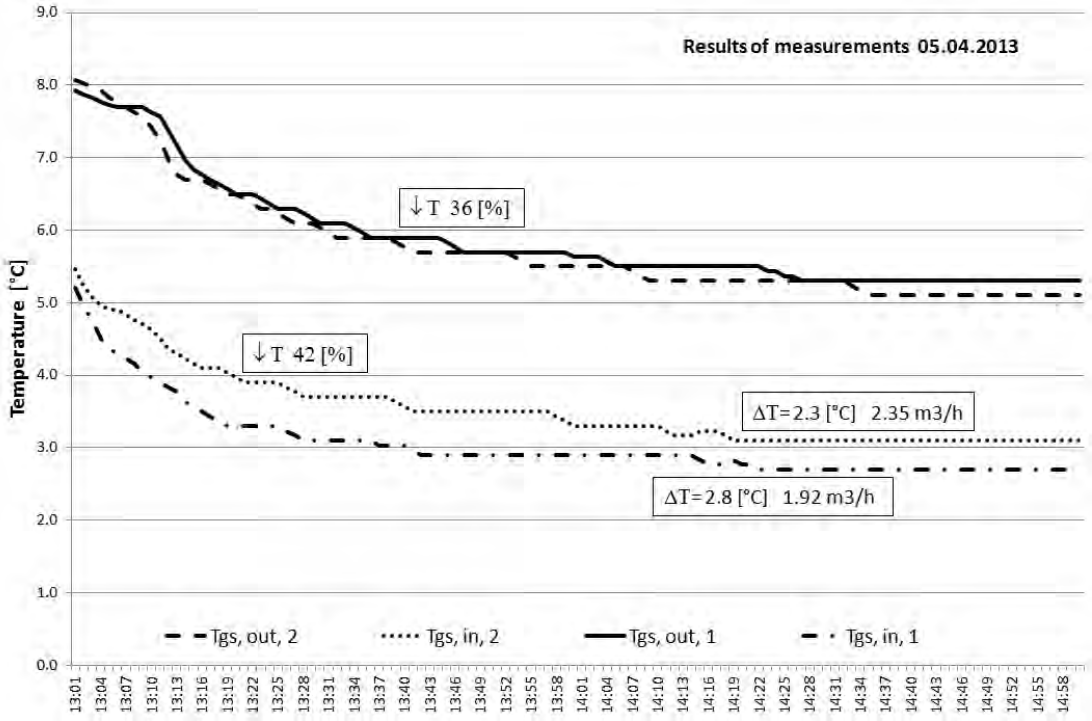


**Fig. 3.** Changes in the temperature in the ground source circuit for two values of the volumetric flow of glycol – 1.92 and 2.35 m3 h-1

brine temperature upstream and downstream of the evaporator. A drop in the temperature of the brine at the inlet to the evaporator remains constant. The recorded temperature of the brine at the inlet to the evaporator reaches the maximum possible temperature resulting from the temperatures of the ground around the vertical collectors. Identical demand for cooling power in the evaporator for two measurement cycles forced a greater temperature difference of ΔTgs=2.8 °C for the volumetric flow of glycol of 1.92 m3 $h^{-1}$.

For all three vertical collectors activated the average temperature difference between the inlet to and outlet from the evaporator on the level of ΔTgs=2.1 °C was recorded along with a drop in the glycol temperature at the inlet to the evaporator on the level of 25%. For two collectors activated simultaneously, the values were ΔTgs=2.9 °C and 38% respectively. Such an examination allows evaluating the dynamics of changes of the operating parameters of the ground source if one of the vertical collectors fails.

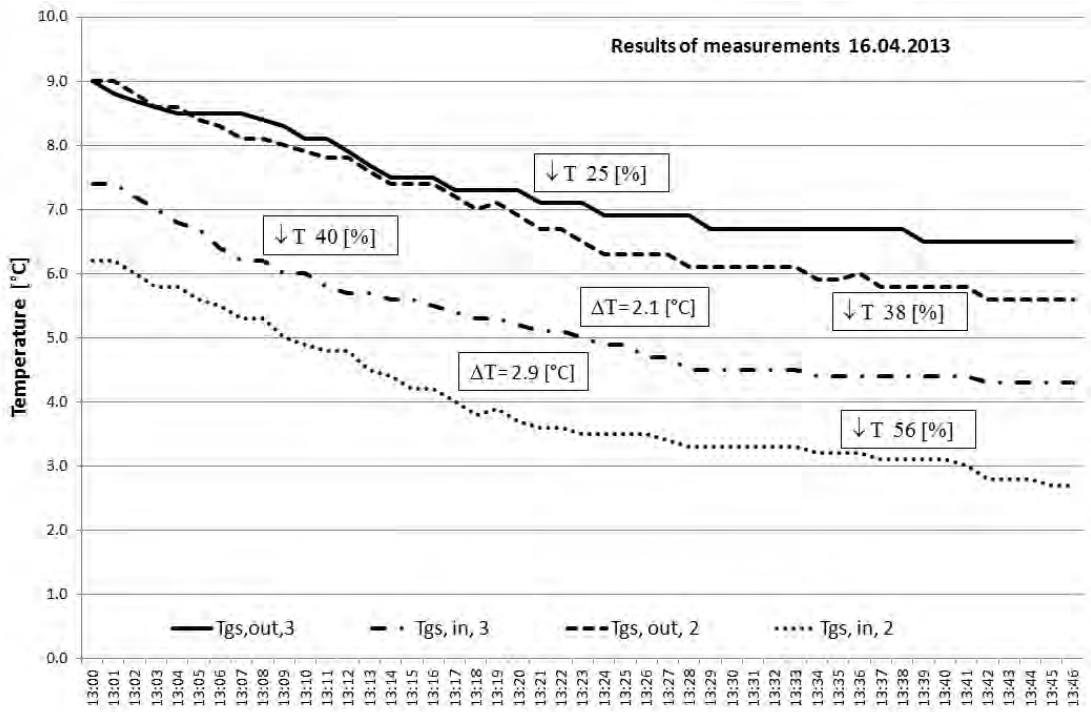


**Fig. 4.** Changes in the temperature in the ground source circuit if one of the collectors is disabled

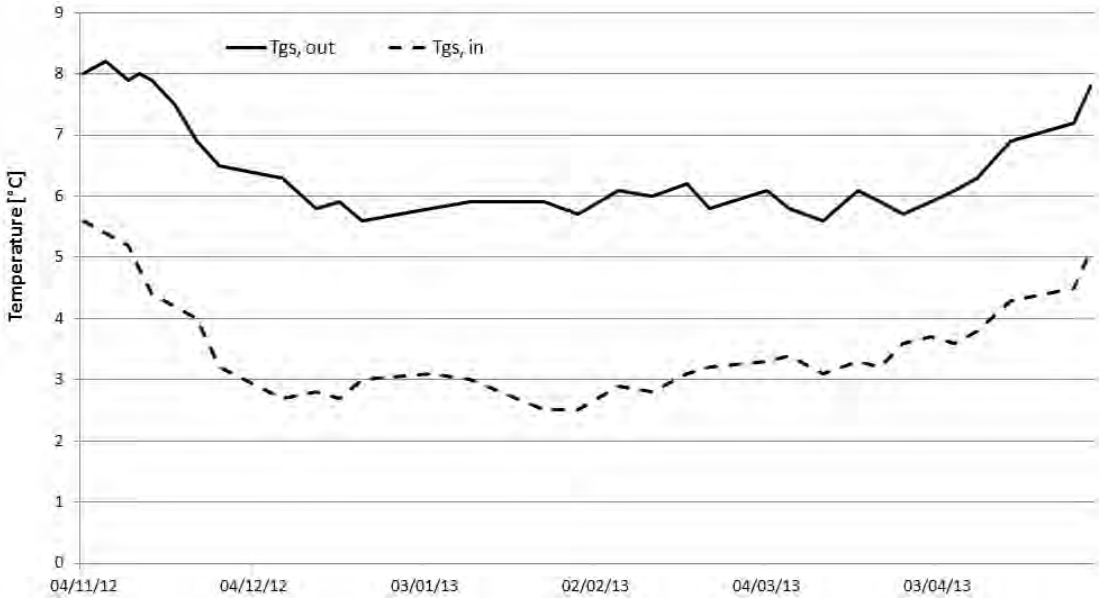


**Fig. 5.** Changes in the temperature in the glycol circuit in the heating season

In the heating season, an increased demand for heat results in a chilling of the ground around the vertical collectors, which manifests itself by a reduction of the glycol temperature at the inlet to the evaporator. As shown in the trend in Fig. 5, the lowest temperature values were observed from December through March (the greatest demand for heat). Usually, in March, the demand for heat drops drastically, the effect of which is a growth in the average temperatures of the glycol circuit.

Fig. 6 presents the trend in the changes of temperature in the glycol circuit for cycle 2 (operation time 2 h, dwell time 1 h). From the analysis of the presented data, we may conclude that the adopted heat pump dwell time is sufficient for the ground temperature around the vertical collectors to stabilize. Additionally, the figure shows the course of changes of the floor temperature when the heating circuit on the ground floor is on.

## CONCLUSIONS

The circuit pumps applied in the experiment consumed on average 35 W (speed 1) and 50 W (speed 2). The total power consumption of the pumps was 3.5 % of that of the compressor.

As the R407C refrigerant evaporation temperature grew, the COP increased but in the case of the tested heat pump,

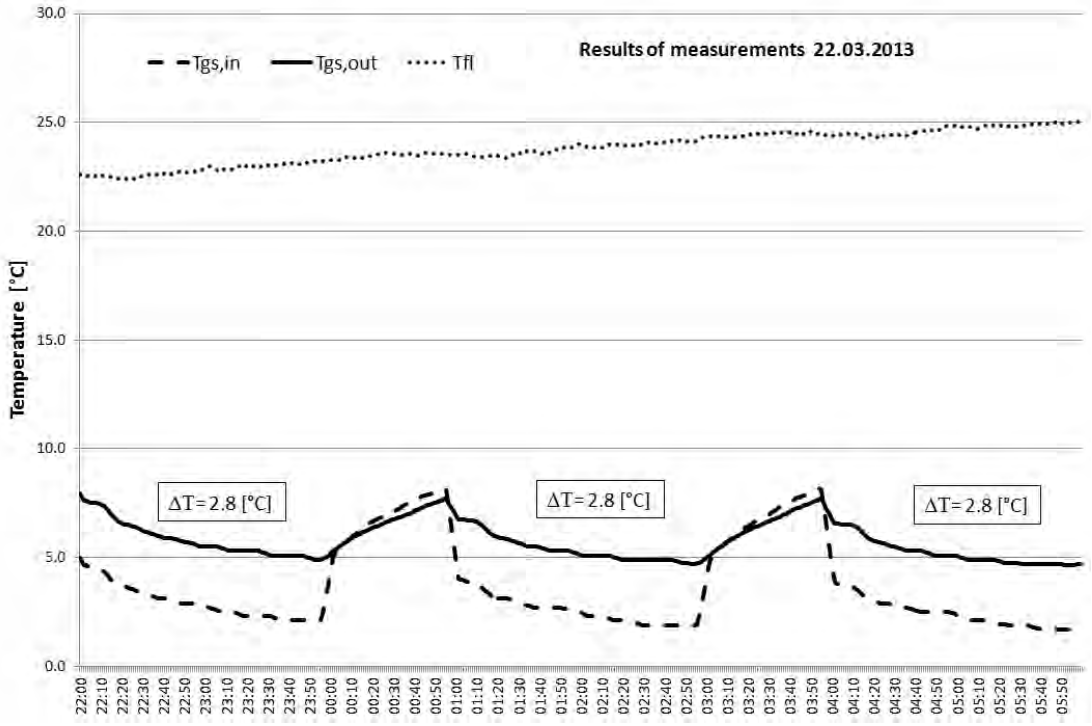


**Fig. 6.** Changes in the temperature in the glycol circuit for cycle 2

the maximum values of COP were obtained for the refrigerant evaporation temperature in the range from –2.5 °C to 0 °C. The obtained results were heavily influenced by the temperature of glycol in the ground source circuit.

The capacity of the heat pump in the tested period changed in the range from 8.4 kW to 9.2 kW. Higher values were obtained for the case of a simultaneous heating on the first and second floors. Setting higher values of the water mass flow in the space heating circuit forces a reduction of the condensation temperature, which leads to an increase in the COP and heating capacity.

From the presented research results, it follows that the total length of the vertical collectors was sufficient to match the cooling capacity of the heat pump. The application of three vertical collectors allows further operation of the heat pump even if one of the collectors fails.

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## BADANIA WYMIENNIKA GRUNTOWEGO POMPY CIEPŁA

**Streszczenie.** W pracy zostały zaprezentowane wybrane zagadnienia dotyczące badania wymiennika gruntowego pompy ciepła zainstalowanej w domu jednorodzinnym wykonanym w technologii niskoenergetycznej. Przeprowadzone badania eksperymentalne na stanowisku badawczym (domek jednorodzinny z ogrzewaniem podłogowym) pozwolą oszacować wpływ wybranych parametrów eksploatacyjnych wymiennika gruntowego na sprawność energetyczną pompy ciepła.
**Słowa kluczowe:** gruntowa pompa ciepła, kolektor pionowy, sprężarka spiralna, źródło dolne, współczynnik efektywności energetycznej.

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# Kinetics Modelling Service Verification of Vehicle Speed Using the Statistical Significance in an Urban Food Distribution

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**Summary.** This paper presents the results of statistical analysis of the mathematical significance of the speed transition phases changes in operational conditions. The analysis was based on tachograph speed recording waveforms obtained in the conditions of urban food distribution. It has been shown that the smallest statistical variability of cooling cars speed waveforms involves a reaction of drivers in urban transport infrastructure.
**Key words:** energy consumption in transport, urban food distribution, speed, acceleration and deceleration phases, statistical significance of overlap.

## INTRODUCTION

Transport food economy forces the fulfillment of specific requirements and transport solutions in terms of quality of services offered and the associated costs. This includes time requirements, which include speed (time) of delivery and timeliness [9, 10].

The speed of delivery is an important requirement, since the short time has its definite advantages, such as [13, 15, 17]:
- kick-start of the production or sale of the product,
- short rotation of current assets frozen during the transport of goods,
- less risk of damage during transportation (e.g. animals – stress, weight loss, etc.),
- possibility to reduce storage space or the number of stationary points for stock along the route,
- possibility to obtain a higher price for high quality promptly-transported fruits, vegetables, dairy products, etc.,
- increase of the market competitiveness of plant or animal products.

An extremely important factor, demonstrating the quality of transport services in the food industry is the safety of cargo, which also depends on the environment in which the transport takes place. The type of environment has a big impact especially in road transport, with a significant share in the transport of food, due to possible collisions and accidents etc. It may take place on congested and frequently bad roads and in varying weather conditions.

The issue of energy consumption in transport, due to the far-reaching consequences for the environment, is currently an important research issue, not only for the environment of transport routes, but especially for the environment of urban agglomeration [6, 8, 12, 16 , 20].

The kinetic phases of speed acceleration and deceleration play an important role in the issues of vehicle motion theory related to power consumption in vehicles [21]. The general considerations on their character can be found in the works by Silkie [18, 19], and they have been verified by urban and extra-urban tests. However, as studies by other authors have shown [1, 2, 3], during smooth driving under operating conditions the operator – vehicle driver must show many non-standard features and high efficiency in the following areas: reception of information, its processing and execution of the decision. Implementation of the decision is the final effect of determining driving style, which is recognized by tachograph record [4].

## THE AIM OF STUDY

As is clear from the review of literature on these issues, in particular, research on energy-intensive vehicles or transport psychology, at present there is no unified theory based on mathetical significance of the interaction of many factors. There is no theory which would explain exhaustively (at the appropriate probability level of its occurrence) a complete behavioral mechanism of a person driving a vehicle on the road or operating a machine. Nevertheless, there are attempts to quantitatively assess the energy consumption of a vehicle in terms of the relevance of interactions occurring in the already developed model of an Intelligent Transport

System ($ITS_{SAT}$) in the food industry [11], for example, in terms of expenditure of kinetic energy associated with the style of driving in variable road conditions, while operating a vehicle or learning driving, etc.

The aim of the present work is an attempt to determine the energy consumption of a vehicle in terms of quantitative evaluation of its driver's reaction in acceleration and deceleration speed phases in the conditions of town and city food distribution.

## THE RESEARCH METHODOLOGY AND STATISTICAL CALCULATIONS

The basis of the adopted statistical methodology of the general kinetic model phases of acceleration and deceleration speeds [18] was the analysis of the statistical significance of their occurrence in the conditions of transport in town (provincial and district) and city (the capital) infrastructure. Boundaries were evaluated of waveforms of continuous driving speed recorded by tachographs of the vehicles used in accordance with the AETR Agreement [14].

The object of study were refrigerated vehicles used for urban food distribution.

This paper presents the results of research on vehicles in the spatial domain of the considered model. In contrast, studies of vehicles in the time domain will be the subject of further studies after obtaining the proper, statistically significant number of measurements.

To assess the significance of their occurrence, the basic statistical calculations were selected: tests number and then populations, showing significant differences among variables in terms of the mean, median, and measures of variability (variance, standard deviation, coefficient of variation) [5, 22].

## STATISTICAL ANALYSIS OF THE TRANSITION SPEED PHASES IN THE CONDITIONS OF URBAN AGGLOMERATION

### THE BASIC SIZES OF THE SET AND THEIR VARIABILITY CHARACTERISTICS

The basic values of set assessment according to the requirements of traffic engineering [7], i.e, the arithmetic mean and median statistics of speed waveform parameters in Lublin are higher in the acceleration phase (Table 1a), and the characteristics of their changes, i.e, variance, standard deviation, coefficient of variation are higher in the deceleration phase (Table 1b).

The statistical values of speed waveform in Biłgoraj show a similar behavior, assuming essentially higher values for the basic parameters (mean, median) in the acceleration phase (Table 2a). For the parameters describing their variability in the deceleration phase (Table 2b).

The smallest statistical variability of speeds was recorded in Warsaw in the acceleration phase, the coefficient of variation was in the range 7.3 – 16.1 % (Table 3a). This was also confirmed by the deceleration phase, the coefficient of variation was similar: 10.8 – 25.4% (Table 3b).

## TESTING THE SIGNIFICANCE OF DIFFERENCES IN MEANS AND VARIANCES OF STATISTICAL PARAMETERS DURING PHASES OF ACCELERATION AND DECELERATION

The calculation results of t-Student tests (assuming equal means $H_o$: $\mu_1 = \mu_2$) and F- Snedecor tests ( assuming equal variances $H_o$: $\sigma^2_1 = \sigma^2_2$) of the statistical parameters of acceleration and deceleration phase of speed in Lublin, Warsaw and Biłgoraj are shown in Tables 4-6.

**Table 1a.** A set of statistical values of speed waveform (Lublin)

| Specification Number | | Statistical parameters of acceleration phase | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Arithmetic mean | Variance | Standard deviation | Median | Mode | Coefficient of variation [%] | |
| Statistical characteristics of set | Mean | 124,32 | 37,49 | 281,02 | 16,55 | 35,54 | 37,01 | 46,79 |
| | Median | 127 | 38,29 | 255,71 | 15,99 | 37,7 | 35,5 | 42,2 |
| | Variance | 986,58 | 87,61 | 8172,16 | 7,08 | 137,59 | 177,16 | 154,75 |
| | Standard deviation | 31,41 | 9,36 | 90,4 | 2,66 | 11,73 | 13,31 | 12,44 |
| | Coefficient of variation [%] | 25,3 | 25 | 32,2 | 16,1 | 33 | 35,9 | 26,6 |

**Table 1b.** A set of statistical values of speed waveform (Lublin)

| Specification Number | | Statistical parameters of deceleration phase | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Arithmetic mean | Variance | Standard deviation | Median | Mode | Coefficient of variation [%] | |
| Statistical characteristics of set | Mean | 104,16 | 20,30 | 236,34 | 14,6 | 25,69 | 16,41 | 76,13 |
| | Median | 90 | 20,07 | 230,09 | 15,17 | 25,62 | 14,28 | 70,7 |
| | Variance | 2885,84 | 51,84 | 20486,2 | 23,04 | 257,02 | 139,01 | 449,86 |
| | Standard deviation | 53,72 | 7,2 | 143,13 | 4,8 | 16,05 | 11,79 | 21,21 |
| | Coefficient of variation [%] | 51,6 | 35,4 | 60,6 | 32,9 | 62,5 | 71,9 | 27,9 |

**Table 2a.** A set of statistical values of waveform speeds (Biłgoraj)

| Specification Number | | Statistical parameters of acceleration phase | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Arithmetic mean | Variance | Standard deviation | Median | Mode | Coefficient of variation [%] | |
| Statistical characteristics of set | Mean | 132,63 | 43,44 | 313,61 | 17,19 | 42,57 | 74,06 | 40,41 |
| | Median | 141 | 40,85 | 277,6 | 16,66 | 43,1 | 60 | 38,8 |
| | Variance | 5273,66 | 98,21 | 26351 | 18,06 | 669,77 | 2072,07 | 101 |
| | Standard deviation | 72,62 | 9,91 | 162,33 | 4,25 | 25,88 | 45,52 | 10,05 |
| | Coefficient of variation [%] | 54,8 | 22,8 | 51,8 | 24,7 | 60,8 | 61,5 | 24,9 |

**Table 2b.** A set of statistical values of waveform speeds (Biłgoraj)

| Specification Number | | Statistical parameters of deceleration phase | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Arithmetic mean | Variance | Standard deviation | Median | Mode | Coeficient of variation [%] | |
| Statistical characteristics of set | Mean | 96,47 | 22,76 | 327,65 | 17,29 | 28,98 | 31,07 | 83,71 |
| | Median | 62 | 18,97 | 276,92 | 16,64 | 25,63 | 23,33 | 77,8 |
| | Variance | 4356 | 149,57 | 39223,8 | 28,62 | 278,56 | 1457,71 | 580,33 |
| | Standard deviation | 66 | 12,23 | 198,05 | 5,35 | 16,69 | 38,18 | 24,09 |
| | Coefficient of variation [%] | 68,4 | 53,7 | 60,5 | 30,9 | 57,6 | 122,9 | 28,8 |

**Table 3a.** A set of statistical values of waveform speeds (Warsaw)

| Specification Number | | Statistical parameters of acceleration phase | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Arithmetic mean | Variance | Standard deviation | Median | Mode | Coefficient of variat [%] | |
| Statistical characteristics of set | Mean | 148,2 | 56,54 | 241,12 | 15,48 | 60,1 | 55,09 | 27,56 |
| | Median | 150 | 56,3 | 249,72 | 15,8 | 58,14 | 57,06 | 26,8 |
| | Variance | 245,86 | 17,14 | 1498,46 | 1,61 | 33,64 | 68,06 | 12,6 |
| | Standard deviation | 15,68 | 4,14 | 38,71 | 1,27 | 5,8 | 8,25 | 3,55 |
| | Coefficient of variation [%] | 10,6 | 7,3 | 16,1 | 8,2 | 9,7 | 15 | 12,9 |

**Table 3b.** A set of statistical values of waveform speeds (Warsaw)

| Specification Number | | Statistical parameters of deceleration phase | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Arithmetic mean | Variance | Standard deviation | Median | Mode | Coefficient of variation [%] | |
| Statistical characteristics of set | Mean | 137,2 | 22,54 | 553,13 | 23,29 | 10,16 | 5,85 | 106,8 |
| | Median | 144 | 23,72 | 571,49 | 23,91 | 9,72 | 6,15 | 99 |
| | Variance | 218,45 | 26,52 | 19773,9 | 10,56 | 1,17 | 1,74 | 241,18 |
| | Standard deviation | 14,78 | 5,15 | 140,62 | 3,25 | 1,08 | 1,32 | 15,53 |
| | Coefficient of variation [%] | 10,8 | 22,8 | 25,4 | 14 | 10,7 | 22,6 | 14,5 |

The calculation results of t-Student test on the driving speed in Lublin ( Table 4), did not show significant differences in case of variance and standard deviation. For other statistical parameters, significant differences were observed. For example, for the speed mode the obtained value $t_{obl}$ = 5,68 lies both in the critical area K = (1,67; ∞) for one-tailed test ( the alternative hypothesis $H_1$: $\mu_1 > \mu_2$) ), and in the critical area K = (-∞; -2) U (2; ∞) for two-tailed test (alternative hypothesis $H_1$: $\mu_1 \neq \mu_2$). The size of the difference calculated according to the relevant literature [22 ] is 13,34 $< \mu_1 - \mu_2 <$ 27,86, which shows that the mean speed mode in the acceleration phase is higher than the mean speed mode in the deceleration phase at least by about 13.34 km/h, and at most by 27.86 km/h ( level of significance α = 0.05).

The calculation results of t-Student test for the significance of occurrence of acceleration and deceleration speed phases in Biłgoraj (Table 5 ) are as follows: in the case of variance ($t_{obl}$ = -0,23) and standard deviation ($t_{obl}$ = -0,06) there are no significant differences for one-tailed [$H_1$: $\mu_1 < \mu_2$; K = (-∞; -1,69)] and two-tailed [$H_1$: $\mu_1 < \mu_2$; K = (-∞; -1,69)] tests. In the case of the median at the significance level α = 0.05 ( two-tailed test ) there are no significant difference, but on the significance level α = 0.1 ( one-tailed test ) there are.

Calculations of the significance of differences between means at acceleration and deceleration speed phases in Warsaw (Table 6 ) showed that for all the statistical parameters they are significant. For example, the difference between the median speed means at acceleration and deceleration

**Table 4.** The calculation results of t-Student and F- Snedecor tests on statistical parameters during speed phases of acceleration and deceleration in Lublin

| Specification | Arithmetic mean | Median | Mode | Variance | Standard deviation | Coefficient of variation |
|---|---|---|---|---|---|---|
| | Max/Min | Max/Min | Max/Min | Max/Min | Max/Min | Max/Min |
| Mean | 37,49/20,34 | 35,54/25,69 | 37,01/16,41 | 281,02/236,34 | 16,55/14,6 | 46,79/76,13 |
| Variance | 87,61/51,84 | 137,59/257,02 | 177,16/139,01 | 8172,16/20486,2 | 7,08/23,04 | 154,75/449,86 |
| Observation | 25/25 | 25/25 | 25/25 | 25/25 | 25/25 | 25/25 |
| Test of t-Student for difference of means: | | | | | | |
| $df/t_{obl}$ | 48/7,11 | 48/2,43 | 48/5,68 | 48/1,29 | 48/1,64 | 48/-5,85 |
| $t_{\alpha=0,1}$ (one-tailed test) | 1,67 | 1,67 | 1,67 | 1,67 | 1,67 | 1,67 |
| $t_{\alpha=0,05}$ (two-tailed test) | 2,0 | 2,0 | 2,0 | 2,0 | 2,0 | 2,0 |
| Test of F-Snedecor for difference of variance: | | | | | | |
| $df_1;df_2/F_{obl}$ | 24;24/1,69 | 24;24/1,87 | 24;24/1,91 | 24;24/2,51 | 24;24/3,25 | 24;24/2,91 |
| $F_{\alpha=0,05}$ | 1,98 | 1,98 | 1,98 | 1,98 | 1,98 | 1,98 |

**Table 5.** The calculation results of t-Student and F- Snedecor tests on statistical parameters during speed phases of acceleration and deceleration in Biłgoraj

| Specification | Arithmetic mean | Median | Mode | Variance | Standard deviation | Coefficient of variation |
|---|---|---|---|---|---|---|
| | Max/Min | Max/Min | Max/Min | Max/Min | Max/Min | Max/Min |
| Mean | 43,44/22,76 | 42,57/28,98 | 74,06/31,07 | 313,61/327,65 | 17,19/17,29 | 40,41/83,71 |
| Variance | 98,21/149,57 | 669,77/278,56 | 2072,07/1457,71 | 26351/39223,8 | 18,06/28,62 | 101/580,33 |
| Observation | 19/19 | 19/19 | 19/19 | 19/19 | 19/19 | 19/19 |
| Test t-Student for difference of means: | | | | | | |
| $df/t_{obl}$ | 36/5,57 | 36/1,87 | 36/3,07 | 36/-0,23 | 36/-0,06 | 36/-7,04 |
| $t_{\alpha=0,1}$(one-tailed test) | 1,69 | 1,69 | 1,69 | 1,69 | 1,69 | 1,69 |
| $t_{\alpha=0,05}$ (two-tailed test) | 2,03 | 2,03 | 2,03 | 2,03 | 2,03 | 2,03 |
| Test F-Snedecor for difference of variance: | | | | | | |
| $df_1;df_2/F_{obl}$ | 18;18/1,52 | 18;18/2,4 | 18;18/1,42 | 18;18/1,49 | 18;18/1,58 | 18;18/5,75 |
| $F_{\alpha=0,05}$ | 2,22 | 2,22 | 2,22 | 2,22 | 2,22 | 2,22 |

**Table 6.** The calculation results of t-Student and F- Snedecor tests on statistical parameters during speed phases of acceleration and deceleration in Warsaw

| Specification | Arithmetic means | Median | Mode | Variance | Standard coefficient | Coefficient of variability |
|---|---|---|---|---|---|---|
| | Max/Min | Max/Min | Max/Min | Max/Min | Max/Min | Max/Min |
| Mean | 56,54/22,54 | 60,1/10,16 | 55,09/5,85 | 241,12/553,13 | 15,48/23,29 | 27,56/106,8 |
| Variance | 17,14/26,52 | 33,64/1,17 | 68,06/1,74 | 1498,46/19773,9 | 1,61/10,56 | 12,6/241,18 |
| Observation | 5/5 | 5/5 | 5/5 | 5/5 | 5/5 | 5/5 |
| Test t-Student for the difference of means: | | | | | | |
| $df/t_{obl}$ | 8/10,29 | 8/16,9 | 8/11,79 | 8/-4,28 | 8/-4,48 | 8/-9,95 |
| $t_{\alpha=0,1}$ (one-tailed test) | 1,86 | 1,86 | 1,86 | 1,86 | 1,86 | 1,86 |
| $t_{\alpha=0,05}$ (two-tailed test) | 2,31 | 2,31 | 2,31 | 2,31 | 2,31 | 2,31 |
| Test F-Snedecor for difference of variance: | | | | | | |
| $df_1;df_2/F_{obl}$ | 4;4/1,55 | 4;4/28,75 | 4;4/39,11 | 4;4/13,19 | 4;4/6,56 | 4;4/19,14 |
| $F_{\alpha=0,05}$ | 6,39 | 6,39 | 6,39 | 6,39 | 6,39 | 6,39 |

phases is in the range $43.13 < \mu1 - \mu2 < 56.75$ ( significance level $\alpha = 0.05$).

Also, the null hypothesis was verified, of equality of variances $H_0 : \sigma^2_1 = \sigma^2_2$ against the alternative hypothesis $H_1$: $\sigma^2_1 > \sigma^2_2$, tj., i.e. the value $F_{obl} = n_1 \sigma^2_1/n_1 - 1 : n_2 \sigma^2_2/n_2 - 1$ [22] was determined.The critical area designated from the arrays of F – Snedecor test is $K = (F_{\alpha=0,05}; \infty)$. In the range of mean, median and mode of the acceleration and deceleration speed phases in Lublin ( Table 4), the calculated values of the test function are, respectively, $F_{obl} = 1,69$, $F_{obl} = 1,87$ and $F_{obl} = 1,91$ and they lie outside the critical area $K = (1,98; \infty)$. Hence, the variance values of these variables are not significantly different, and the null hypothesis was fulfilled. In the case of the city Bilgoraj (Table 5), for the median and coefficient of variation there are significant differences ($F_{obl} > F_{\alpha=0,05}$), for the other statistical parameters there are none. Furthermore, the verification calculations of the hypothesis of equality of variance between the driving speeds during acceleration and deceleration phases in Warsaw (Table 6) showed that only for the mean velocity range it is true is, i.e. $F_{obl} = 1,55 < F_{\alpha=0,05} = 6,39$.

## CONCLUSIONS

The analysis of electronic record of a vehicle's speed in the urban conditions of food distribution allows for the shortening of transport by the fast, optimal selection of both the vehicle and route for a specific transport task . The basis is to optimize the driving technique of the vehicle ( traction parameters ). So, study on the use of electronic analysis of the operation are used to determine energy-efficient ( economic ) driving routes in the distribution of food products, e.g. from the manufacturer ( wholesaler ) to the collection point, which is now an important transport problem for cities and may increase transportation costs.

The developed research material in the field of kinetic energy expenditure during the acceleration and deceleration speed phases allowed for the determination of both the general conclusions of cognitive nature and the specific ones as to the obtained statistical significance of changes in the boundary of tachograph recording waveform in the conditions of urban food distribution.

## COGNITIVE CONCLUSIONS

1. Tachograph record is the basic, technical, legislative and final record of the driver's reaction, which reflects both the kinetics of the vehicle and the characteristic features studied by the transport psychology.
2. In place of the previously used models of kinetic energy expenditure, or the driver's psychological models, the in-service model type should be used, the so-called Intelligent Transportation System based on the SAT system, taking into account both the interactions occurring in space ( statistical number of vehicles on the section of the infrastructure ) and the time domain, considering the long term "energetic reactions" of the driver
3. Analysis of energy consumption of the vehicle associated with the style of its operation is an important factor in the impact of transport on the environment in every urban and transport infrastructure.

## SPECIFIC CONCLUSIONS AND DEVELOPMENT

1. The smallest variability of the analyzed statistical parameters expressed in coefficient of variation was obtained for the speeds waveform in Warsaw, in both kinetic phases. In smaller cities (Lublin, Biłgoraj, coefficients of variation reach higher values.
2. The basic statistical values of the set (mean, median) are higher in the acceleration phase, and their variability factors (variance, standard deviation, coefficient of variation) assume higher values in the speed deceleration phase.
3. The tests of difference significance for the means of the analyzed parameters showed significant differences in both speed phases in Warsaw. For the other cities, no significant difference exists only in the case of variance and standard deviation of speed in acceleration and deceleration phases. In the case of median there is no clear cut.
4. Verification of the hypothesis of equality of variances of the two speed phases in Lublin showed that it met the basic statistical parameters, while significant differences concerned the parameters assessing their variability. Equality of variance occurred only in the case of mean speed in Warsaw, and in relation to the speed waveform in Biłgoraj it concerns not only the median and coefficient of variation.

On the basis of the obtained specific conclusions it should be noted that the food distribution drivers' behavior in urban infrastructure points at energy-efficient driving, and thus lower harmful impact on the environment. This is also related to better solutions for transport infrastructure, longer sections of continuous driving, using the green line, etc. [7].

The mathematical analysis of statistical significance gives a quantitative assessment of change at a given level of probability, and the use of digital recording (up to 40 000 sampling values) provides basically endless possibilities for research that will continue in studies realized in the food industry.

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## EKSPLOATACYJNA WERYFIKACJA MODELOWANIA KINETYKI PRĘDKOŚCI JAZDY POJAZDU METODĄ ISTOTNOŚCI STATYSTYCZNEJ W WARUNKACH MIEJSKIEJ DYSTRYBUCJI ŻYWNOŚCI

**Streszczenie.** W pracy przedstawiono wyniki statystycznej analizy matematycznej istotności zmian faz przejściowych prędkości jazdy w warunkach eksploatacyjnych. Analizę przeprowadzono w oparciu o oscylogramy zapisu tachograficznego prędkości jazdy, uzyskane w warunkach miejskiej dystrybucji żywności. Wykazano, że najmniejsza zmienność parametrów statystycznych oscylogramu prędkości jazdy samochodów chłodniczych dotyczy reakcji kierowców w wielkomiejskiej infrastrukturze komunikacyjnej.

**Słowa kluczowe:** energochłonność transportu, miejska dystrybucja żywności, prędkość jazdy, fazy przyspieszania i opóźniania, istotność statystyczna zachodzenia.

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# Characteristics of the Functioning of Agricultural Products Transportation Networks

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**Summary.** The management of complex transportation networks of agricultural producers requires the centralisation of management. In the study we present the method of determination of simple economic characteristics of complex transportation networks in the form of a few optimisation barriers. They reflect the border values of the parameters of the network operating under various management methods. The interpretation of the achieved barriers was provided. The methodology of the assessment of the synergy effect of the operation of the agricultural producer group was indicated. A relevant example was presented.
**Key words:** optimisation, multistage transportation problem, centralisation of management, producer groups.

## INTRODUCTION

## TRANSMISSION CENTRALISATION PROBLEMS IN THE AGRICULTURAL TRANSPORTATION NETWORK

The use of operational research methods in the agricultural economics problems as well as in the agricultural and food industry has been dealt with in subject literature on a number of occasions. The transportation issue in agriculture as well as the agricultural and food industry can be viewed upon in various aspects. It can be a decisive factor as regards the location of the agricultural and food production facilities or it can optimise transportation costs incurred in the existing structure of the agricultural transportation network. For example Platt [15], Siarkowski et al [16] indicate the mathematical programming models used for the needs of the dairy industry while determining the range of products and in the dairy transportation problems, whereas Nowicka-Skowron [14], Baryła-Paśnik et al [2] presents heuristic models used in dairy transportation. Kłapeć and Marszałkowicz [8] use multi-stage transportation problems for the needs of forest economy. Marczuk [10÷13] considers the problems of transportation of agricultural products and deals with inter alia the determination of the quantity of the means of transport necessary for the execution of transportation tasks [see also 9]. Ignaciuk and Wawrzosek [7] touch upon the new issues regarding the optimisation of transportation as regards agricultural producer groups [18÷21]. They indicate new possibilities of the application of various tools of operational research, including modified models of multi-stage problems for the needs of determining the economic justifiability of adopting the rules applicable to the members of a producer group and regarding the transport of agricultural products. In this study the authors refer to the methodology of this article. They consider here different conditions resulting this time from the network capacity. They address the issue of the cost effectiveness of synergistic actions taken up by a number of entities through the operation of producer groups. Moreover, they compare the cost effectiveness of joint management as regards decentralised way of product transportation. At the same time, the authors stress the fact that centralised management within an agricultural producer group is connected with the costs of its implementation and maintenance.

The continuous improvement of suboptimum operating parameters of the entire transmission network entails using simple indices of improvement of its operation that should reflect the most significant economic features connected with the network at issue. In the study it is indicated that the method of determining economic characteristics of usually complex transportation networks should refer to existing optimization barriers. The optimization barriers determined in this study constitute border values of parameters which can be achieved by the network under management decentralization conditions.

***A multistage transportation problem*** *(MTP*) is a transportation problem consisting in moving one, uniform type of goods from consignors (sources) to consignees (destinations), where the transportation can be effected via other nodes (that are not ultimate consignees). *MTP* can be presented in a graphic way as a transportation network.

## SYMBOLS

Each of $n$ nodes $o_i$ (i = 1,2,...,$n$) for *MTP* is characterised by coefficient: $p_i$ – i.e. a difference in the supply possibility and demand possibility of a given node. If the difference between the supply and demand possibility is:

1. $p_i > 0$ for $1 \le i \le n_1$ it means that $n_1$ nodes are ***consignors (sources)*** $\boldsymbol{S_i}$,
2. $p_i = 0$ for $n_1 + 1 \le i \le n_1 + n_2$, then a node cannot stop incoming goods i.e.. $n_2$ nods are ***intermediate storage facilities (warehouses)*** $\boldsymbol{W_i}$,
3. $p_i < 0$ for $n_1 + n_2 + 1 \le i \le n_1 + n_2 + n_3 = n$ it means that $n_3$ nodes are ***consignees (destinations)*** $\boldsymbol{D_i}$.

$\boldsymbol{A}$ – a set of ordered pairs $(i, j)$ for which there exists a possibility of transportation between $i$-th and $j$-th node of the *MTP* network, where we assume a priori that $(i,i) \notin \mathbf{A}$, for each $1 \le i \le n$ (we assume that the shipping from $o_i$ node to itself is not possible). Set $\boldsymbol{A}$ constitutes a fragment – a subset of square matrix elements $\boldsymbol{A}_0$ of dimension $n \times n$.

$c_{i,j}$ – unit transport cost between $i$-th and $j$-th node *MTP* for $(i, j) \in \boldsymbol{A}$. We assume that such a cost is always nonnegative.

$d_{i,j}$ – capacity between $i$-th and $j$-th *MTP* node for $(i, j) \in \boldsymbol{A}$.

$x_{i,j}$ – decision variables determining the quantity of goods shipped between $i$-th and $j$-th *MTP* node for $(i, j) \in \boldsymbol{A}$.

Additionally the sums of $x_{i,j}$ for all columns and rows of matrix $\boldsymbol{A}_0$ (the sums of $x_{i,j}$ for members of the set $\boldsymbol{A}$) of decision variables are denoted by:

$k_j = \sum_{\substack{(i,j)\in A \\ 1\le i\le n}} x_{i,j}$ (total quantity of goods supplied to the $j$-th *MTP* node),

$r_i = \sum_{\substack{(i,j)\in A \\ 1\le j\le n}} x_{i,j}$ (total quantity of goods shipped from the $i$-th *MTP* node),

$u_i = r_i - k_i$ (difference between the quantity of shipped and received by the $i$-th *MTP* node).

## MATERIAL AND METHODS

### CHARACTERISTICS OF THE TRANSPORTATION NETWORK

The transportation network as regards economic transportation indices is characterised by three particular parameters:

1. $m_T$ maximum transmission of the network (quantity of goods that can be transported in a definite time from consignors to consignees via storage facilities),
2. $f_{\min}(m_T)$ minimum cost of transport executing the maximum transmission of the network,
3. $f_{\max}(m_T)$ maximum cost of transport executing the maximum transmission of the network,

as well as two basic functions that characterise the network $f_{\min}(m)$ and $f_{\max}(m)$ for transmission execution level $m$, where $0 \le m \le m_T$. Function $f_{\min}(m)$ corresponds to the centralised and optimum network management in an economical way, whereas function $f_{\max}(m)$ describes a maximally uneconomical way of operating the network (which can be achieved while employing central, expedient management). Function $f(m)$ is such that $f_{\min}(m) \le f(m) \le f_{\max}(m)$ dependent on the transmission execution level $m$ corresponds to the decentralization in the network management.

The ways to estimate possible functioning of the network can be the function plot being the average $\frac{f_{\min}(m) + f_{\max}(m)}{2}$, range $f_{\max}(m) - f_{\min}(m)$ or ratio $\frac{f_{\min}(m)}{f_{\max}(m)}$. To give an example, while considering that the range $f_{\max}(m) - f_{\min}(m)$ to function $f_{\min}(m)$ ratio takes on small values as compared to the costs of network control or the ratio $\frac{f_{\min}(m)}{f_{\max}(m)}$ is close to one there is a need to consider a possibility of abandoning centralised management of the network. An example where some of the above network characteristics for a multistage transportation problem *MTP* have been analysed is presented at the end of the study.

## TWO-PHASE ALGORITHM

Below a two-phase algorithm was proposed for *MTP*. This algorithm modifies classical transportation models of linear programming [1, 3÷6, 8, 13, 17, 22÷24]. Its first phase consists in determining the ***maximum transmission of*** $m_T$ ***network*** from established consignors to consignees (see Definition 2 below), whereas the second phase by optimizing the total shipping costs determines the following:

1. optimum goods transport plan,
2. network characteristics defined above,

at the determined (not necessarily maximum) use of its transmission capacity. The concurrent examining of the minimum and maximum shipping cost in the second phase is connected with the consideration of the centralised and decentralised network management mentioned at the beginning.

***The maximum transmission of*** transportation ***network*** $m_T$ is the maximum quantity of goods that can be transported at a given *MTP* in a network with $o_i$ from the consignors (sources) through storage facilities to consignees (destinations) while complying with limitations imposed as to the demand and supply possibilities and route capacity i.e. weight limitations regarding both nodes $o_i$ and arches $(o_i, o_j)$ of a graph.

### PHASE 1: DETERMINATION OF THE MAXIMUM TRANSMISSION IN THE NETWORK

Model ***MTP–P1***:

*ObjF* (maximum transmission of the network): $m_T = \sum_{1\le i\le n_1} u_i \to \max$,

*LC-P*1 were presented in Table 1.

**Table 1.** Presentation of limiting conditions for phase 1 of the algorithm; model MTP–P1.

| Nodes | Shipping – receiving |
|---|---|
| Consignors (sources) | $0 \le u_i \le p_i$ |
| Intermediate storage facilities | $u_i = 0$ |
| Consignees (destinations) | $p_i \le u_i \le 0$ |

*LC-C* (capacity ): $x_{i,j} \le d_{i,j}$ for each pair $(i,j) \in \boldsymbol{A}$,
*BC*: $x_{i,j} \ge 0$ for each pair $(i,j) \in \boldsymbol{A}$.

PHASE 2: OPTIMUM COST OF TRANSPORT

***Transmission execution level*** (*T.E.L.*) is any number $m$ such that $0 \le m \le m_T$.

Model ***MTP–P2***:

*ObjF* (minimisation or maximisation of the total transport cost in the network for selected $m$ as *T.E.L.*):

$$f_{\min}(m) \text{ or } f_{\max}(m) = \sum_{\substack{(i,j)\in A \\ 1\le i,j\le n}} x_{i,j} \cdot c_{i,j} \to \min \text{ or } \max,$$

$$LC\text{-}P2: \begin{cases} LC\text{-}P1, \\ LC\text{-}C, \\ LC\text{-}T.E.L. \text{ (determined } T.E.L. \text{ in the network): } \sum_{1\le i\le n_1} u_i = m \end{cases}$$

*BC*: $x_{i,j} \ge 0$, for each pair $(i,j) \in \boldsymbol{A}$.

*LC-P2* is composed of *LC-P1* and *LC-C* complemented by an additional condition *LC-T.E.L.* that can guarantee achieving *T.E.L.* at $m$ level.

## RESULTS AND DISCUSSION

### EXAMPLE OF USE OF THE CHARACTERISTICS OF THE TRANSPORTATION NETWORK OF AN AGRICULTURAL PRODUCER GROUP

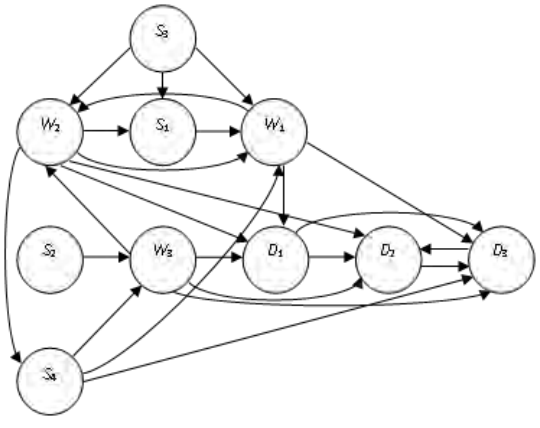


**Fig. 1.** Directed graph with weights on edges and nodes

The agricultural producer group is engaged in the goods transportation in the network presented graphically in Figure 1. The weights ($c_{i,j}$, $d_{i,j}$) were collected in Table 2 as two sparse matrices. Weights ($p_i$) are column vectors in Table 2. Table 2 also contains a sparse matrix $x_{i,j}$ of the solution minimising of the total shipping costs for *T.E.L.* of $m = m_T = 56$ goods units. The minimum transport costs for $m = 56$ goods units amount then to 3216 monetary units. Let us notice that (Table 2) the limiting conditions *LC-C* $x_{i,j} \le d_{i,j}$ are fulfilled.

### THE MAXIMUM AND THE MINIMUM SHIPPING COSTS FOR THE AGRICULTURAL PRODUCER GROUP

The analytical tools of economic aspects of network transmission considered here are directly or indirectly connected with two basic functions $f_{\min}(m)$ and $f_{\max}(m)$, describing, respectively, the minimum and maximum total costs of network transportation for *T.E.L.* in the amount of $m$. These functions enable the economic assessment of the network transportation possibilities without getting into its detailed structure and they allow uncomplicated comparison of networks. At the same time the presented characteristics allow the examination of the options of the network structure as regards the assumed parameters. The relevant characteristics of the network for the presented example were presented in graphs (Figure 1), created using a two-phase algorithm for the transportation network. All necessary calculations can be made using any optimisation software.

### ABSOLUTE AND RELATIVE COST-EFFECTIVENESS OF THE OPTIMISATION OF THE AGRICULTURAL PRODUCT TRANSPORTATION

Let us define the cost-effectiveness of transportation optimisation.

***The absolute indicator of cost-effectiveness of network transportation*** $E_A(m)$ at the set execution level of transmission $m \in (0, m_T)$ is the difference:

$$E_A(m) = f_{\max}(m) - f_{\min}(m). \tag{1}$$

***The relative indicator of cost-effectiveness of network transportation*** $E_R(m)$ at the set level of transmission execution $m \in (0, m_T)$ is the quotient:

$$E_R(m) = \frac{f_{\min}(m)}{f_{\max}(m)} \cdot 100\%. \tag{2}$$

## CONCLUSIONS

1) The presented example can constitute a miniature of complex systems and refers only to the transportation in the determined time unit.
2) The network is characterised by two economic barriers in the form of functions $f_{\min}(m)$ and $f_{\max}(m)$. They describe the minimum and the maximum transportation cost obtained by adopting various ways of the network management. The minimum one corresponds to the desired effect of management. The maximum one would mean possible greatest losses related to ineffective transportation in the network (Figure 2). An additional economic barrier that characterises the network is the maximum transmission $m_T$.

**Table 2.** Adjacency table for transportation network in the analysed example

| $c_{i,j}:d_{i,j}:x_{i,j}$ | $S_1$ | $S_2$ | $S_3$ | $S_4$ | $W_1$ | $W_2$ | $W_3$ | $D_1$ | $D_2$ | $D_3$ | $r_i$ | $p_i$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $S_1$ | | | | | 10;8;8 | | | | | | 8 | 21 |
| $S_2$ | | | | | | | 34;8;8 | | | | 8 | 11 |
| $S_3$ | 13;11;0 | | | | 37;13;5 | 37;16;16 | | | | | 21 | 21 |
| $S_4$ | | | | | 46;8;0 | | 27;7;7 | | | 34;12;12 | 19 | 24 |
| $W_1$ | | | | | | 28;6;2 | | 22;5;5 | | 31;6;6 | 13 | 0 |
| $W_2$ | 39;7;0 | | | 19;12;0 | 22;6;0 | | | 29;8;8 | 36;10;10 | | 18 | 0 |
| $W_3$ | | | | | | 36;9;0 | | 32;5;4 | | 38;12;11 | 15 | 0 |
| $D_1$ | | | | | | | | | | 20;6;0 | 0 | -17 |
| $D_2$ | | | | | | | | | | 16;5;0 | 0 | -12 |
| $D_3$ | | | | | | | | | 38;10;0 | | 0 | -35 |
| $k_j$ | 0 | 0 | 0 | 0 | 13 | 18 | 15 | 17 | 10 | 29 | | |

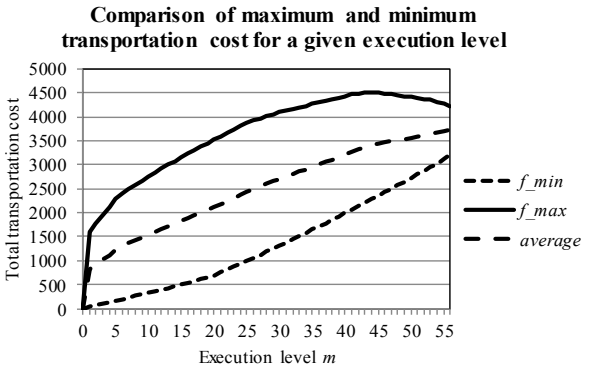


**Fig. 2.** Graphs of function $f_{\min}(m)$ and $f_{\max}(m)$ as well as function $\frac{f_{\min}(m)+f_{\max}(m)}{2}$ constituting their arithmetic mean

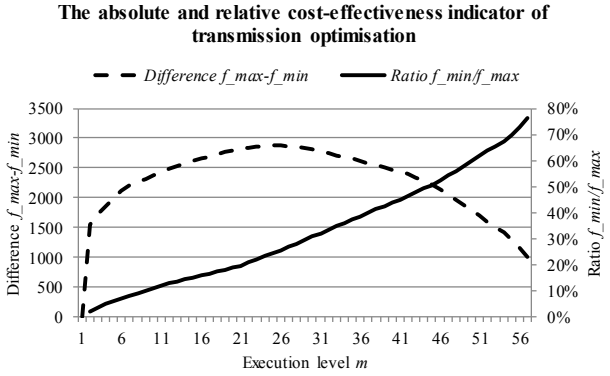


**Fig. 3.** Graphs of functions $E_A(m)=f_{\max}(m)-f_{\min}(m)$ and $E_R(m)=\frac{f_{\min}(m)}{f_{\max}(m)}\cdot 100\%$ for the analysed example

3) The barriers named in item 2) constitute the limitation to the possible realisations of network operation while adopting various ways of management (Figure 2).
4) The lack of centralised control of the entire network poses a loss risk. The loss extreme size is described by the function $E_A(m)$. These losses should be compared to the costs of various forms of network management, which do not constitute the subject matter of this study (Figure 3).
5) The absolute cost-effectiveness ratio of transportation optimisation in the examined network reaches the highest value 2879 within the range of 24 – 25 of transmission units. It means that decentralization or suboptimum control risk increase up to the threshold of 24 – 25 transfer units. The negative results of the decentralization of agricultural transportation network control decrease along with the transfer increase beginning from this threshold value (Figure 3).
6) In Figure 2 we can notice that for 44 transmission units the function $f_{\max}(m)$ reaches the highest value of 4518. Beginning from this level of transmission execution we can additionally observe the coercion of more effective self-organising of network transportation which is described by the decrease of function value $f_{\max}(m)$. The self-organising of network is forced by free market competition.
7) For the maximum transmission $m_T$ the greatest losses resulting from management decentralisation do not exceed 1008 of monetary units. For $m_T$ the minimum costs of transportation accounts for 76% of the maximum cost, which justifies the concern for optimum parameters of transportation, whereas including the costs of centralised management for transmission close to the limit value ($m_T$) can sometimes suggest abandoning the central control even of a relatively small network.
8) Knowing the cost appropriated for transportation ( e.g. 2000 units) within the producer group, the graph of the function $f_{\min}(m)$ (Figure 2) can show the limit level of the execution of transmission (in this case 40 units). This level can be achieved only the most efficient method of network management is applied.
9) The awareness of economic barriers in the form of maximum network transmission capacity and the relevant function of $f_{\min}(m)$ and $f_{\max}(m)$ type prevents submitting erroneous requirements both from the members of the producer group and the coordinator of the operation of the entire network.
10) The awareness of these barriers enables one to control the process of improvement of the management of the agricultural producer group transportation network.

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## CHARAKTERYSTYKI FUNKCJONOWANIA SIECI TRANSPORTU PRODUKTÓW ROLNYCH

**Streszczenie.** Zarządzanie złożonymi sieciami transportowymi grup producentów rolnych wymaga centralizacji zarządzania. W pracy wskazuje się sposób wyznaczania prostych charakterystyk ekonomicznych złożonych sieci transportowych w postaci kilku barier optymalizacyjnych. Odzwierciedlają one wartości graniczne parametrów sieci pracującej przy różnych sposobach zarządzania. Podano interpretację uzyskanych barier. Wskazano metodykę oceny efektu synergicznego działania grupy producenckiej. Zaprezentowano odpowiedni przykład.

**Słowa kluczowe:** optymalizacja, wieloetapowe zagadnienie transportowe, centralizacja zarządzania, grupy producenckie.

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# The Effect of Fiber Addition on the Extrusion-Cooking Stability and Quality of Enriched Corn Snacks

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**Summary.** The paper presents the results of measurements of process efficiency and energy consumption during the extrusion-cooking of corn snacks enriched with fibers and the effect of additives on the texture of snacks. For enriched extruded snacks corn meal was used as base raw material and various types of fiber were added: wheat bran, barley bran, oat bran and inulin from chicory, in an amount of 5, 10, 15 and 20% of sample mass. Extrusion was performed using a single screw extruder TS-45, L/D=16:1 at a screw speed of 120 rpm. During processing the determined efficiency and specific energy consumption were registered depending on the additives applied. To evaluate the texture Warner – Bratzler knife was used to determine the cutting forces of extrudates. There was a higher process efficiency during the extrusion of corn snacks with rye bran addition, and greater specific energy consumption was determined during the extrusion of snacks with addition of wheat and oat bran. The best crunchy characteristic and low hardness was evaluated for corn snacks enriched with oat bran in an amount from 5 to 15%.
**Key words:** extrusion-cooking, snacks, cereal bran, energy consumption, texture.

## INTRODUCTION

One of the popular snacks are crunchy corn snacks produced using extrusion-cooking technology, which is the modern method of production of a wide range of food and feed products. This method allows for the production of products based on vegetable raw materials, like crisps and puffs, pellets, breakfast cereals, instant noodles, modified starches, pet food and fish feed and many others [6, 9, 14, 15, 25].

Implementation of extrusion-cooking technology has allowed manufacturers to enrich food products with all kinds of additives which enabled to vary the products in terms of physical properties, taste and nutritional properties. The introduction of new types of additives allows for continuous development of the wide range of extruded products. These additives affect not only the extrudates properties, but also on the thermo-mechanical treatment conditions and characteristics of the process [1, 5, 6, 10, 19, 20]. Extrusion-cooking process increases the soluble fiber fractions content, as well as affect on antioxidant activity of obtained extrudates [3, 4, 16, 18].

Nowadays, with the intensity of the civilization diseases, scientists began to explore functional additives that allow to improve the nutritional characteristics of products or give it healthy characteristics [2, 19, 25]. One of such additive is a fiber that is present in the whole grain cereal milling products, in the bran from outher layer of cereal seeds and specially prepared high-fiber preparations isolated from plant parts, like inulin from Chicory [17]. Dietary fiber is a valuable component of the low-fat diet, helps maintain adequate level of sugar in blood and body weight.

The benefits of fiber consumption are primarily to protect against the development of coronary heart disease and many cancers, reducing the level of bad cholesterol in the blood, and it has beneficial effects on insulin level protects against diabetes type 2 [16, 18, 19]. Fibres, although valuable for health, cannot be absorbed in raw form, e.g. in the form of unprocessed bran, because it contains phytates limiting minerals uptake, which disappear after heating

The impact of the pressure-thermal treatment during snacks extrusion-cooking can reduce to a minimum the influence of unfavorable components to the body and at the same time allows for significant improvement of extruded products stability [23]. Selection of the appropriate extrusion-cooking conditions makes it possible forming and shaping of the final product characteristics, affects the expansion of the material, the creation of porous structure and shape of final extrudates [9, 18, 19, 21, 25].

The aim of the study was to determine the process efficiency and specific energy consumption during the extrusion-cooking of corn snacks enriched with varying amounts of fibers from wheat bran, rye bran, oats bran and inuline, and an effect of fiber addition on texture of products.

## MATHERIALS AND METHODS

As a basic material corn grits was used (protein – 11.39%, fat – 1.06%, ash – 1.65%, fiber – 9.3%). Wheat bran, rye bran and oat bran were ground in a laboratory grinder to particle size less than 1 mm, inulin was powdered. Mixtures of raw materials containing added wheat bran, rye bran, oat bran (Sante, Sobolew) and inulin ( ) at 5, 10, 15 and 20% of the sample mass has been prepared. Raw materials were moistened and mixed to obtain a moisture content of 14%. After mixing the raw materials were processed using a modified single screw extruder TS-45 (Metalchem, Gliwice, Poland) with L/D=16:1, compression ratio 3:1, at a temperature range from 120 to 150°C [7]. Snacks were shaped using a die with a hole having 3 mm in diameter. During the extrusion-cooking process efficiency and specific energy consumption SME was evaluated in triple for each recipe [12, 22].

Produced corn snacks with addition of different formulations of fiber functional additives were tested for texture; hardness was defining as the maximum force during the cutting test. For cutting test universal testing machine Zwick BDO-FB0.5TH (Zwick GmbH & Co. KG, Ulm, Germany) was used with a Warner-Bratzler knife (1 mm thick) to determine the force [21, 23, 25]. The cutting force evaluation was carried out depending on the type and amount of additive used in snacks formulations. Single snack was placed on the table at 90° relative to the cutting blade and tested. Cutting force value $F_{max}$ was determined at the moment of sample breakage. The distance between the grips during the test was 210 mm. Tests were carried out at a head speed of 100 mm·min$^{-1}$ in 10 replications.

Based on the data collected during multiple measurements the influence was determined of type and amount of additives on the tested parameters and the relationship between the tested characteristics by determining the regression equations and correlation coefficients [8]. Polynomial correlation coefficients were determined and statistical analysis was performed using Statistica 6.0 software determining the significance of differences between the means and the p- values at confidence interval of 95% using the F test.

## RESULTS

The extrusion-cooking process of corn snacks with the addition of various fibers proceeded uniformly; there were no disturbances in raw materials feeding, or large temperature fluctuations for the tested formulations with fiber addition. The collected snacks were characterized by an even surface, and the expansion was dependent on the type and amount of fiber additive used in the recipe. The process efficiency of the extrusion-cooking of snacks was determined in triplicate for each part of the processed materials, the measurement results are shown in Figure 1. Process efficiency during the extrusion-cooking of snacks with added bran showed a tendency to decrease with increasing participation of bran in the recipe. For all of the additives significant differences were observed in process efficiency (Table 1). Efficiency at

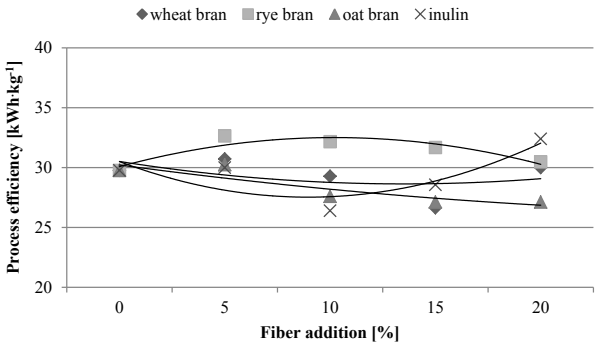


**Fig. 1.** Process efficiency of processing of corn snacks with various type and amount of fiber additives

120 rpm and 14% of initial moisture content of raw materials varied in the range of 26 to 34 kg·h$^{-1}$.

The most intensive lowering of process efficiency was determined during the extrusion-cooking of snacks with oat bran and rye bran addition. For extrudates with rye bran addition the highest efficiency was determined over the entire range of applied shares. In the case of wheat bran additive, decreased efficiency was noted when the additive was used in 15% of the sample weight, application of 20% amount of wheat bran in the formulation increased process efficiency to the level obtained for corn snacks without additives. During efficiency measurements of snacks processed with the addition of inulin a significant reduction was observed of the tested parameter when 10% of additive was used, whereas further increasing of the amount of inulin in the formulations influenced the increase in efficiency of the process. Generally, it can be stated that the use of fiber additives in an amount of 5% in the recipe resulted in increasing the efficiency of the extrusion-cooking process of enriched corn snacks.

There were also negative correlations between the process efficiency and the specific mechanical energy requirements during extrusion-cooking of snacks with additions of fibers; particularly high values of correlation coefficients were determined during the analysis of the measurements results of snacks with the addition of wheat bran, oat bran and inulin (Table 2). Wójtowicz and Juśko [20] leading efficiency testing of extrusion-cooked precooked pasta with using of single screw extruder reported for commercial refined wheat flour the lowest process efficiency (12 kg·h$^{-1}$) and the highest efficiency was achieved during the extrusion-cooking of whole wheat flour and spelt pasta, even up to 32 kg·h$^{-1}$.

SME values, designated as the specific mechanical energy requirements during extrusion-cooking of corn snacks enriched with cereal bran and inulin ranged from 0.23 to 0.31 kWh·kg$^{-1}$ and depended both on the type and on the quantity of fiber additive used. The measurement results are summarized in Figure 2. The differences between the values of the SME were small, but statistically significant (Table 1). Only at using rye bran as additive the results were not significantly different at a given level of significance (p-value= 0.068). The highest SME values were determined during the extrusion-cooking of snacks with added wheat bran and oat bran in the amount of 15% in the mixture of raw materials. The greater amount of bran caused a slightly lower specific energy requirement ($R^2 = 0.968$).

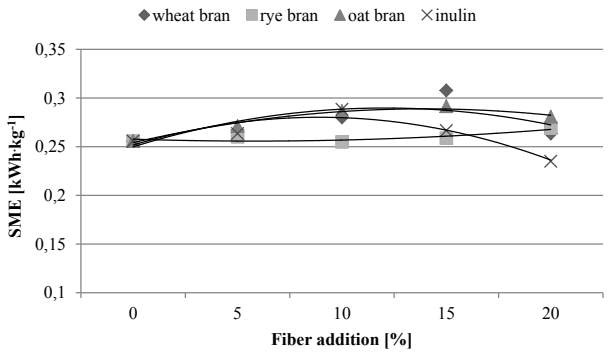


**Fig. 2.** SME values during processing of corn snacks with various type and amount of fiber additives

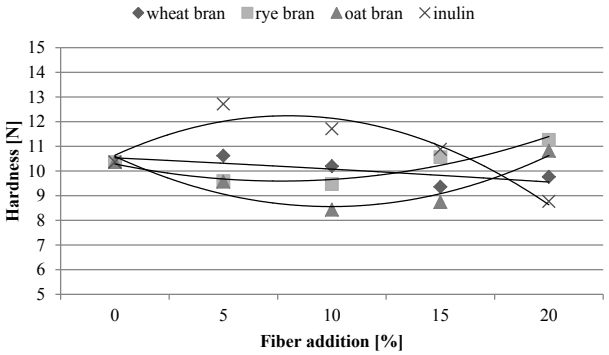


**Fig. 3.** Hardness of extruded corn snacks with addition of various types and amount of fibers

During the single screw extrusion-cooking of different botanical origins of starch the observed SME remained in the range of 0.083 to 0.275 kWh·kg$^{-1}$ for potato starch [12] , 0.075-0.297 kWh·kg$^{-1}$ was the energy consumption of wheat starch [13] and 0.08-0.29 kWh·kg$^{-1}$ was determined using corn starch [11] depending upon the processing parameters. Stojceska and coworkers [19] used the twin screw extruder for the manufacture of snack products containing red cabbage and brewery wastes. SME for these extrudates varied from 0.06 to 0.10 kWh·kg$^{-1}$ for extrusion-cooking of corn starch snacks with brewery wastes, while the use of cabbage waste addition decreased SME values to the level from 0.029 to 0.035 kWh·kg$^{-1}$. Additionally, the higher the moisture content of raw materials, the lower requirements of SME were. By using cauliflower waste as a fiber source in snacks SME values were obtained ranging from 0.07 to 0.13 kWh·kg$^{-1}$, depending on the conditions of the extrusion-cooking process [18].

Altan and others [1] obtained the SME values from 0.16 to 0.37 kWh·kg$^{-1}$ during the extrusion-cooking of barley meal snacks containing tomato skins as a source of fiber, which declined with increasing temperatures and lower screw rotational speed. SME values determined during the extrusion of precooked pasta using a single screw extruder TS-45 at the initial moisture content of 30% ranged from 0.06 to 0.21 kWh·kg$^{-1}$ and depended both on the raw materials used (purified or whole grain flour) and extrusion-cooking screw speed applied [20]. The highest SME was determined when purified spelt flour was used, a greater amount of fiber resulted in lower specific mechanical energy requirements during the extrusion-cooking of instant pasta.

To measure the hardness of snacks in the present work cutting test was used, the hardness was determined as the maximum force required to break the sample [21]. Figure 3 shows the results of cutting force measurements of snacks enriched with various types and amount of fibers. The moisture content of snacks, important when assessing texture characteristics of the tested products, ranged from 7.8 to 8.5%, proper for the storage stability of processed cereals and did not cause any deterioration of their crispness.

Cutting force of corn snacks reached 10.36 N, supplementation of snacks with fiber enrichments resulted in a differentiated way on the hardness of snacks extruded with the addition of various bran types and inulin. Using wheat bran, increasing the amount of additive resulted in lowering the hardness, the lowest cutting forces were determined during testing of snacks with 15% of wheat bran in the recipe, but the differences between the measurements were not statistically significant (Table 1). Similar trends were observed using oat bran as additive in an amount up to 15%, while increasing the share of this additive up to 20% resulted in an increase of snacks hardness. Application of rye bran in an amount not exceeding 10% also resulted in a reduction of cutting force of extrudates, a greater amount of the additive significantly increased the hardness of the tested snacks ($R^2$=0.919). Inulin used as an additive resulted

**Table 1.** The results of statistics and significance of differences for the tested parameters of enriched corn snacks depend on fiber type used

| Tested characteristic | Fiber type | Equation of regression | $R^2$ | F test values | p |
|---|---|---|---|---|---|
| Process efficiency | wheat bran | $y = 0{,}257x^2 - 1{,}903x + 32{,}16$ | 0,227 | 139,377 | 0,0000 |
| | rye bran | $y = -0{,}583x^2 + 3{,}545x + 27{,}12$ | 0,836 | 96,835 | 0,0000 |
| | oat bran | $y = 0{,}086x^2 - 1{,}354x + 31{,}488$ | 0,783 | 769,425 | 0,0000 |
| | inulin | $y = 0{,}925x^2 - 5{,}170x + 34{,}752$ | 0,702 | 201,274 | 0,0000 |
| SME | wheat bran | $y = -0{,}007x^2 + 0{,}049x + 0{,}219$ | 0,586 | 41,243 | 0,0000 |
| | rye bran | $y = 0{,}001x^2 - 0{,}007x + 0{,}274$ | 0,746 | 3,078 | 0,0680 |
| | oat bran | $y = -0{,}004x^2 + 0{,}035x + 0{,}234$ | 0,968 | 40,017 | 0,0000 |
| | inulin | $y = -0{,}009x^2 + 0{,}052x + 0{,}219$ | 0,854 | 40,343 | 0,0000 |
| Hardness | wheat bran | $y = -0{,}008x^2 - 0{,}195x + 10{,}738$ | 0,603 | 1,474 | 0,2257 |
| | rye bran | $y = 0{,}296x^2 - 1{,}502x + 11{,}495$ | 0,919 | 3,024 | 0,0272 |
| | oat bran | $y = 0{,}513x^2 - 3{,}069x + 13{,}150$ | 0,886 | 6,648 | 0,0003 |
| | inulin | $y = -0{,}625x^2 + 3{,}253x + 8{,}013$ | 0,911 | 6,947 | 0,0002 |

in the greatest differences in the hardness of snacks; with the addition of inulin in amount from 5 to 15% hardness of extrudates was higher than corn crisps without additives (10,9-12,8 N) and the increase of additive up to 20% resulted in a significant decrease in hardness of snacks (8.8 N). In this case a significant decrease was observed of the cutting force with increasing amount of inulin in the mixture of raw materials ($R^2 = 0.910$).

The radial expansion ratio of extrudates, which also affected the results of cutting force measurements, reached the value of 5.8-4.7 for snacks with the addition of wheat bran, 5.7-4.3 in the case of rye bran, 5.8-4.8 when oat bran was used and 5.5-4.1 using the additive of inulin. The greater the bran additive in the recipe formulation of raw materials, the lower expanding of snacks was observed, only the addition of inulin in an amount of 20% resulted in expansion increase, which had also the effect of lowering the hardness of snacks determined in the cutting test. The hardness of snacks was also correlated with the process efficiency results depending on the type of bran applied, most significantly for snacks enriched with wheat bran (Table 2). The relationships were also visible when determining the correlation of SME values with the results of snacks hardness, in this case also depending on the bran type.

**Table 2.** Correlation coefficients of relationships between the tested parameters depend on the fiber type used

| Evaluated parameter | Fiber type | | | |
|---|---|---|---|---|
| | wheat bran | rye bran | oat bran | inulin |
| SME/Efficiency | -0,906 | -0,205 | -0,826 | -0,979 |
| SME/Hardness | -0,716 | 0,734 | -0,606 | 0,744 |
| Efficiency/Hardness | 0,827 | -0,690 | 0,234 | -0,610 |

Comparing the obtained results with the literature data it can be concluded that the lower hardness of snacks enriched with fiber was obtained in the presented study. Corn snacks enriched with addition of defatted flax seeds processed with single screw extrusion-cooker using a similar processing conditions showed hardness values in the range of 10 to 32 N, the higher forces required for breakage of extrudates were determined at a higher speed test. The highest hardness was determined during the cutting test of snacks enriched with addition of 10 and 12.5% of flax seeds [25]. Corn-buckwheat snacks processed under similar conditions with the addition of buckwheat in an amount from 10 to 50% showed an increase of the cutting forces with the increase of the amount of additive from 18.4 to 23.3 N [21]. For these products, the lowering of expansion ratio was observed from 6.5 to 5.1 with increasing participation of buckwheat in the mixture of raw materials, which probably increased the hardness of snacks.

For precooked pasta fortified with wheat bran addition lowering of the hardness was determined during the cutting of dry pasta with the increasing amount of bran in the mixture with values varied from 16.8 N at 5% bran added to 4.2 N by using 25% of wheat bran in the recipe [23]. The addition of bran to such products led to obtaining a looser internal structure, as confirmed by microstructure analysis, the increased portion of bran component disrupted the formation of a stable structure of starch-protein matrix which is responsible for forming and maintaining the shape of the extrudates. When using twin screw extruder to prepare snacks containing cauliflower waste the hardness was similar to the one presented in the study and ranged from 6.38 to 12.60 N depending on the extrusion-cooking process conditions [18]. The hardness of extruded snacks based on corn starch with brewery waste addition ranged from 8.0 to 14.0 N and using the addition of red cabbage lowered the hardness, which ranged from 5.1 to 8.8 N [19].

## CONCLUSIONS

Investigation of the effect of additives on the process efficiency of fiber enriched corn snacks prepared with the extrusion-cooking process, the demand of SME and texture of corn snacks showed a significant effect of both the type and quantity of cereal bran and inulin on the characteristics of the process and the quality of snacks. Use of single screw extruder TS-45 to produce corn snacks enriched with fibrous additives allowed obtaining products with acceptable texture characteristics at low cost energy. The best texture with the lowest hardness was determined during the test of corn snacks with addition of oat bran at 10 and 15%.

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## WPŁYW DODATKÓW BŁONNIKOWYCH NA WYDAJNOŚĆ I ENERGOCHŁONNOŚĆ PROCESU EKSTRUZJI ORAZ TEKSTURĘ WZBOGACANYCH CHRUPEK KUKURYDZIANYCH

**Streszczenie.** W pracy przedstawiono wyniki pomiarów wydajności oraz energochłonności procesu ekstruzji chrupek kukurydzianych z dodatkiem preparatów błonnikowych oraz wpływ zastosowanych dodatków na teksturę przekąsek. Do wzbogacenia chrupek ekstrudowanych z kaszki kukurydzianej zastosowano różne rodzaje preparatów błonnikowych: otręby pszenne, jęczmienne, owsiane i inulina z cykorii w ilości 5, 10, 15 i 20%. Ekstruzję prowadzono z zastosowaniem ekstrudera jednoślimakowego TS-45 z L/D = 16:1 przy prędkości ślimaka 120 obr·min$^{-1}$. W trakcie ekstruzji wyznaczano wydajność oraz energochłonność procesu określając jednostkowe zapotrzebowanie energii w zależności od zastosowanych dodatków wzbogacających. Do oceny tekstury zastosowano nóż Warner-Bratzler'a do wyznaczenia siły cięcia wzbogacanych ekstrudatów. Obserwowano wyższą wydajność procesu podczas ekstruzji chrupek kukurydzianych z dodatkiem otrąb żytnich, natomiast większą energochłonność wyznaczono podczas ekstruzji chrupek z dodatkiem otrąb pszennych i osianych. Najniższą twardością charakteryzowały się chrupki z dodatkiem otrąb owsianych w ilości od 5 do 15%.

**Słowa kluczowe:** ekstruzja, chrupki, otręby, energochłonność, tekstura.

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