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STEAM AND HEAT CONSUMPTION DURING CONDITIONING OF VEGETABLE FEED RAW MATERIALS IN THE PELLETING PROCESS

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Summary. The paper presents the results of studies on the effects of the parameters of conditioning of selected feed raw materials on the energy consumption of the process. The studies were conducted on a test stand equipped with a microprocessor system measuring steam and heat consumption. The conclusion reached is that the mean values of steam consumption range between 17.03 and 158 $kg \cdot t^{-1}$, while those of thermal energy consumption – from 41.1 to 516.7 $kJ \cdot kg^{-1}$. Among the characteristics distinguishing the treated material, specific heat and bulk density had the most significant impact on heat consumption. The lowest mean demand for thermal energy (91.45 $kJ \cdot kg^{-1}$) was recorded in maize, while the highest (260.4 $kJ \cdot kg^{-1}$) – in lucerne.

Key words: pelleting, conditioning, thermal energy, specific heat

Nomenclature:

a	– thermal expansion coefficient, $[m^2 \cdot s^{-1}]$
c	– specific heat, $[kJ \cdot kgK^{-1}]$
E	– amount of thermal energy consumed during conditioning, [kJ]
E_c	– thermal energy consumption, $[kJ \cdot kg^{-1}]$
m_s	– weight of ground grain exiting the conditioner, [kg]
p	– calculated significance level,
P_p	– steam pressure, [kPa]
r	– Pearson's correlation coefficient
R^2	– coefficient of determination
T_k	– conditioning temperature, $[^oC]$
Z	– amount of steam consumed during conditioning, [kg]
Z_p	– unit steam consumption, $[kg \cdot t^{-1}]$
α_i	– assumed significance level
λ	– specific heat conductivity, $[W \cdot mK^{-1}]$
ρ_n	– bulk density, $[kg \cdot (m^3)^{-1}]$

INTRODUCTION

The amount of steam and heat consumed in the conditioning process depends primarily on the properties and proportions of particular components in feed mixtures – which is related to the material temperature after treatment (usually from 50 to 90°C) as well as to the parameters of process steam [6]. According to Smallman [7], the category of raw materials susceptible to conditioning (i.e. easily absorbing humidity and heat) includes grain as well as high-protein materials with a low fiber content. Fibrous and oil raw materials are less susceptible to this process.

The intensity of heat and mass exchange during hydrothermal treatment results primarily from the thermo-physical properties of the material, i.e. specific heat, specific heat conductivity and thermal diffusivity [2]. As reported by Kaleta [3], these properties – with respect to feed raw materials – are the subject of numerous studies and analysis. However, there are no detailed data regarding the effect of the above properties on the parameters of the conditioning process. Literature on the subject focuses mostly on the role of specific heat, which is related to the remaining heat values by the following dependence:

$$c = \frac{\lambda}{a\rho_n} \qquad [\mathrm{kJ \cdot kgK^{-1}}] \tag{1}$$

Providing the value of specific heat for the most frequently used feed raw materials, Kamiński et al. [4] concluded that this characteristic significantly affects the demand for steam during the pelleting process. It follows that a mixture of raw materials with higher specific heat requires (in order to reach the appropriate temperature for pelleting) a greater addition of water vapor than a mixture of components distinguished by a lower value of this characteristic.

The above findings were partially confirmed by Vandewalle et al. [8] in studies on conditioning lucerne meal and ground maize. These authors found that a higher demand for steam is recorded during the treatment of the first raw material ($c = 2.3$ kJ·kgK^{-1}) compared to the second, which is characterized by a lower specific heat value ($c = 1.9$ kJ·kgK^{-1}).

Determining the thermal energy flux supplied with water vapor during conditioning allows to establish the process energy balance as well as unit thermal energy expenditures on the pelleting technological line. An overview of reference data shows that no comprehensive studies have been carried out so far that would resolve all the issues related to this matter. An aspect that should be pointed out is that the information provided by authors is not in fact confirmed by experimental results, which is due to the lack of test stands equipped with appropriate measuring devices [1]. Therefore, the purpose of this study was to determine steam consumption and thermal energy expenditures during hydro-thermal conditioning of materials of varied physical and chemical properties, at assumed temperature levels acquired as a result of applying steam at various pressure levels.

Despite widespread use of pelleted feeds, so far many process parameters have been determined under production conditions in approximation, or certain parameters (such as steam consumption) have been calculated theoretically only. The need to use new, less expensive raw materials, or to prepare new feed recipes, makes it necessary to search for optimal pelleting process parameters. This kind of research may be conducted with the use of the test stand designed at the Department of Operation of Food Processing Machinery, University of Agriculture, Lublin [5].

MATERIALS AND METHODS

The raw materials were comprised of ground barley, maize, wheat, oat, pea, lupine and lucerne meal. The materials were ground in a hammer mill equipped with a 3 mm mash sieve. After grinding, the materials were brought to a constant moisture content of 14%. The specific heat value (Tab. 1) and bulk density (Tab. 2) were determined for the experimental materials.

Table 1. Mean values of specific heat (c) of raw materials for the moisture content of 14%

Raw material	Barley	Maize	Wheat	Oat	Pea	Lupine	Lucerne
c [kJ·kgK^{-1}]	1.84	1.92	1.81	1.65	1.78	1.91	2.19

Table 2. Mean bulk density values of raw materials (ρ_n) for a moisture content of 14%

Raw material	Barley	Maize	Wheat	Oat	Pea	Lupine	Lucerne
ρ_n [kg·(m^3)$^{-1}$]	467.2	620.3	592.1	303.2	635.4	591.1	130.34

The hydrothermal conditioning treatment was carried out with the use of a blade conditioner [5], at a rotational speed of the shaft of 300 rev/min with the angle of blades with respect to the shaft axis of 15°. The materials were brought to five temperature levels, i.e. 50, 60, 70, 80 and 90°C. The required temperature following hydrothermal processing was achieved in every instance by water vapor treatment under five pressure levels: 200, 250, 300, 350 and 400 kPa. The level of treatment temperature, depending on the type of material and steam pressure, was determined by controlling the intensity of steam supply to the conditioner.

The tests were conducted on a test stand equipped with a computer system, enabling a detailed analysis of the thermal energy demand within the process. A detailed description of the test stand equipment along with the methodology of determining heat and steam consumption is presented in the work of [5].

Unit demand for steam in the conditioning process was determined by calculating the quotient of the amount of the consumed steam and ground grain mass (generated at identical time intervals) according to the following formula:

$$Z_p = \frac{Z}{m_s} \cdot 1000 \quad [\mathrm{kg \cdot t^{-1}}] \tag{2}$$

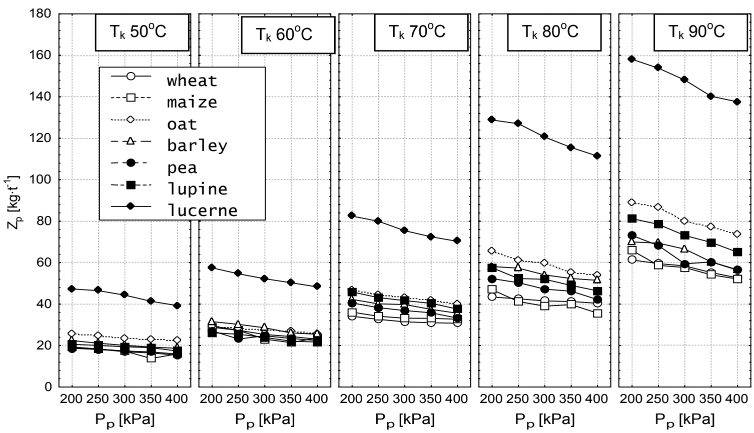
Unit thermal energy expenditures in the conditioning process was calculated from the quotient of the amount of the consumed heat and ground grain mass exiting the conditioner (generated in identical time intervals) according to the following formula:

$$E_c = \frac{E}{m_s} \quad [\mathrm{kJ \cdot kg^{-1}}] \tag{3}$$

An analysis of the dependence between the parameters of the conditioning process and the energy consumption of the process was performed using the statistical procedures included in the STATISTICA program, at a significance level of $\alpha_i = 0.05$. The form of equation was chosen applying backward step regression. The significance of regression equation coefficients was analyzed with the Student's t-test. Model adequacy was verified with the Fisher test. The figures present the results of analysis of the significance of differences (Tukey test) between the mean values of the tested parameters with respect to a given raw material. The raw materials that significantly differ with regard to the mean values of particular parameters are marked by different letters.

RESULTS

Fig. 1. presents the results of steam consumption analysis, as dependent upon the conditioning temperature and steam pressure.



Electrical (pressing) energy consumption during pelleting with steam are shown in Figure 1. Mean values of this parameter varied from 120 to over 200 kJ· kg^{-1}.

The generated values are within a wide range, from 17.03 to 158.82 kg/t. Changes of similar nature were also recorded for unit thermal energy expenditures (Fig. 3). In this case, the mean values fluctuated between 41.1 and 516.47 kJ·kg^{-1}.

Fig. 2 and Fig. 3 show that steam and thermal energy consumption per unit increase along with an increase in temperature during hydrothermal treatment, and that in both cases the dependence takes the form of a second degree polynomial (Tables 3 and 4). It should be stressed that the low values of regression coefficients at variable T_k^2 indicate that the effect of temperature on the values of the analyzed parameters within the tested range is close to the linear form.

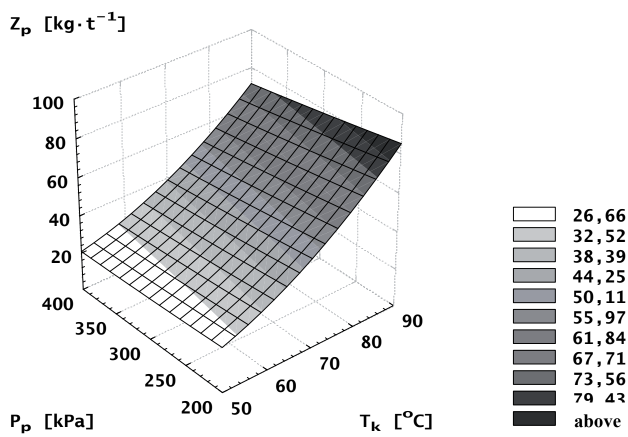


Fig. 2. Dependence of steam consumption (Z_p) on conditioning temperature (T_k) and steam pressure (P_p)

It was also observed that an increase in steam pressure results in a decrease in steam consumption, upon the same values of conditioning temperature. Due to the fact that steam enthalpy at a pressure of 400 kPa (2738 kJ·kg^{-1}) is only slightly under 2% higher than enthalpy corresponding to 200 kPa (2707 kJ·kg^{-1}), while heat and mass exchange takes place under atmospheric conditions, this is most probably a result of greater heat loss taking place when a lower steam pressure is applied.

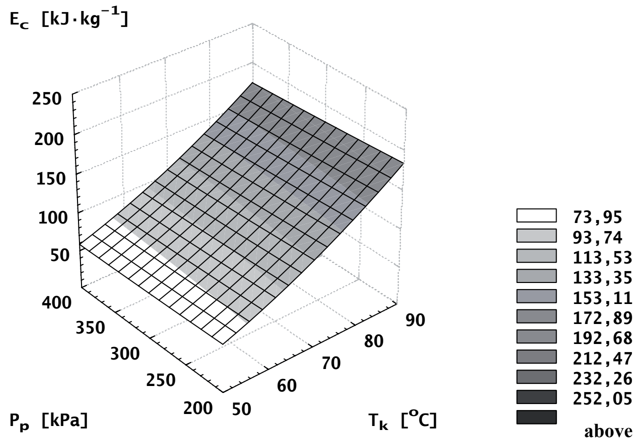


Fig. 3. Dependence of unit thermal energy expenditures (E_c) on conditioning temperature (T_k) and steam pressure (P_p) (mean values for 7 tested raw materials)

It follows that unit thermal energy expenditures also diminish along with the rise in steam pressure. However, it should be stressed that the rate of these changes is slow, amounting to only a 0.035 unit increase in heat consumption per pressure unit, and is on average 14% lower than the rate of steam consumption increase. The equations describing the effects of conditioning parameters on the value of unit steam consumption and unit thermal energy expenditures are presented in Tables 3 and 4.

Table 3. Regression equations describing the effect of conditioning temperature (T_k) and steam pressure (P_p) on steam consumption (Z_p)

RAW MATERIAL	EQUATION	A	B	C	D	R2
Wheat	Zp = ATk2 – BTk - CPp + D	0,0124	0,7796	0,0245	33,24	0,982
Maize	Zp = ATk2 – CPp + D	0,0069		0,0364	10,17	0,972
Barley	Zp = ATk2 – BTk - CPp + D	0,0265	2,24	0,0402	80,97	0,987
Oat	Zp = ATk2 – CPp + D	0,0081		0,0010	5,70	0,985
Pea	Zp = ATk2 – CPp + D	0,0082		0,0395	7,58	0,972
Lupine	Zp = ATk2 – BTk - CPp + D	0,0191	1,32	0,0423	49,55	0,982
Lucerne	Zp = ATk2 – BTk - CPp + D	0,0408	2,95	0,0707	108,19	0,982

Table 4. Regression equations describing the effect of conditioning temperature (T_k) and steam pressure (P_p) on unit thermal energy expenditures (E_c)

RAW MATERIAL	EQUATION		A	C	D	R2
Wheat	Ec = ATk2 – CPp + D	0,0184		0,0359	9,65	0,952
Maize	Ec = ATk2 – BTk - CPp + D	0,0373	2,43	0,0375	88,30	0,982
Barley	Ec = ATk2 – BTk - CPp + D	0,0725	6,13	0,0407	196,68	0,987
Oat	Ec = ATk2 – CPp + D	0,0218		0,0419	12,23	0,991
Pea	Ec = ATk2 – BTk - CPp + D	0,0414	2,50	0,0315	77,13	0,992
Lupine	Ec = ATk2 – BTk - CPp + D	0,0525	3,57	0,0312	105,45	0,99
Lucerne	Ec = ATk2 – BTk - CPp + D	0,2645	27,25	0,011	826,03	0,992

The data presented in Fig. 4 indicate that the lowest demand for steam occurs during the conditioning of ground wheat and maize (no statistically significant differences between the raw materials) and is on average 61% lower than steam consumption recorded for lucerne.

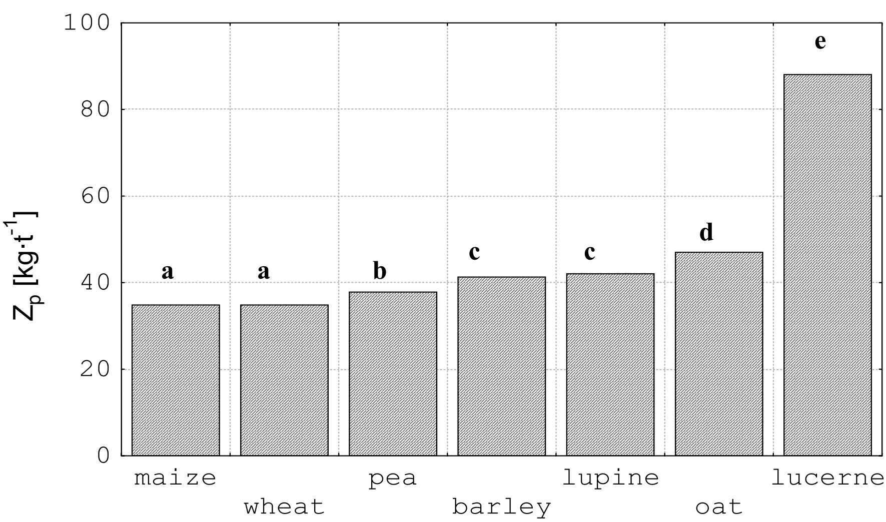


Fig. 4. Dependence of mean steam consumption on the type of raw material (mean values calculated for 5 conditioning temperature levels and 5 steam pressure levels)

Changes of identical nature, depending on the type of raw material, were also observed with regard to the analysis of heat consumption (Fig. 5).

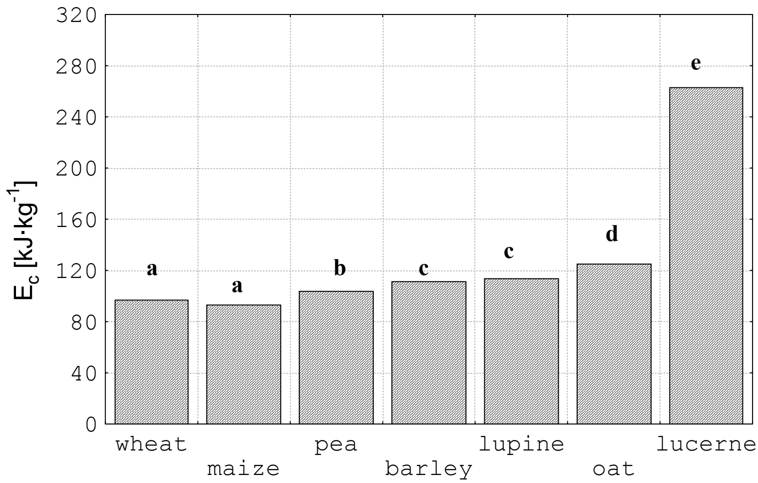


Fig. 5. Dependence of mean unit thermal energy expenditures (E_c) on the type of raw material (mean values calculated for 5 conditioning temperature levels and 5 steam pressure levels)

The statistical analysis based on the obtained results showed that there is a very high positive correlation between steam consumption (r=0.806; p<0.028) as well as heat consumption (r=0.834; p<0.019) and the value of specific heat of the tested raw materials (*c*). However, the predictive value of the obtained regression equations turned out to be insufficient since the values of coefficients of determination amount to, respectively: R^2 = 0.581 for steam consumption and R^2 = 0.636 for heat consumption. As a result, taking into account the above findings as well as the fact that in the conditioning process the material is proportioned by volume, another important parameter affecting steam demand and the value of unit thermal energy expenditures is bulk density (Fig. 6 and 7). It is significant due to the fact that the value of this parameter shows considerable variation depending on the type of raw material (Tab. 2).

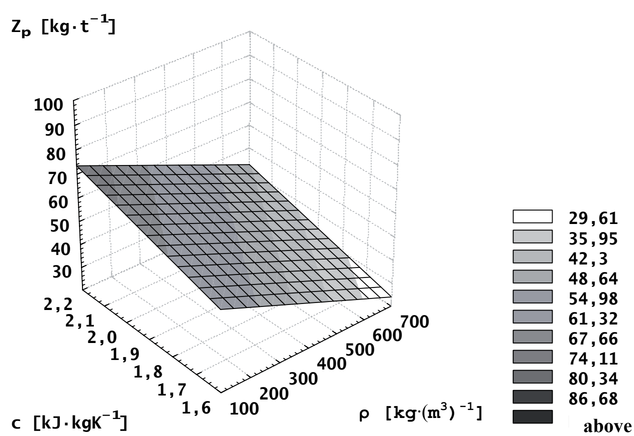


Fig. 6. Dependence of steam consumption (Z_p) on specific heat capacity (c) and bulk density (ρ_n) (mean values for 7 tested raw materials).

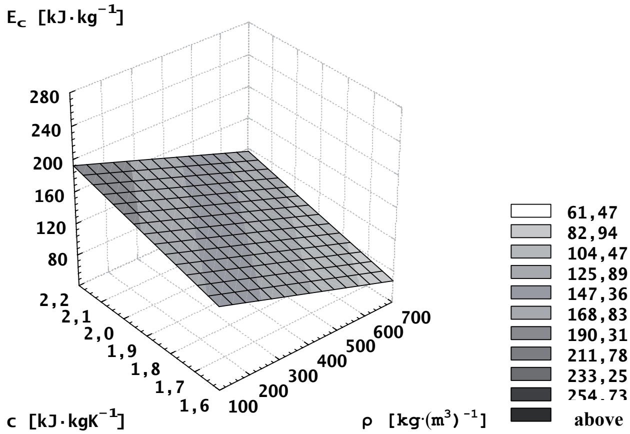


Fig. 7. Dependence of unit thermal energy expenditures (E_c) on specific heat capacity (c) and bulk density (ρ_n) (mean values for 7 tested raw materials)

Figures 6 and 7 show that the increase in steam consumption and in unit thermal energy expenditures is directly proportional to the value of specific heat capacity of the raw material, and inversely proportional to bulk density. As a result, the dependences may be presented in the form of linear multiple regression models:

$$Z_p = 45.03\,c - 0.063\,\rho_u - 8.19;\ R^2 = 0.946 \quad (4)$$

$$E_c = 159.31c - 0.187\,\rho_u - 82.03;\ R^2 = 0.964 \quad (5)$$

CONCLUSIONS

1. Steam consumption in the conditioning process is affected by both temperature of hydrothermal treatment and steam pressure. An increase in conditioning temperature from 50 to 90 °C results in an average increase in steam and heat consumption by 330%.
2. Along with increasing steam pressure, the efficiency of heat and mass exchange during conditioning increases and, in consequence, the value of unit thermal energy expenditures decreases insignificantly.
3. Among the characteristics distinguishing the treated material, specific heat and bulk density have the most significant impact on steam consumption. The obtained dependences take a linear form.
4. The lowest demand for heat is noted during the conditioning of ground wheat and maize (no statistically significant differences between the raw materials) and is on average 63% lower than heat consumption recorded for lucerne.

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