EFFECT OF PARTICLE SIZE OF FRAGMENTED WHEAT ON ENERGY REQUIREMENTS IN THE PROCESS OF EXTRUSION

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Summary. The paper presents the results of a study on the effect of mean particle size on energy requirements in the process of extrusion and on the index of material susceptibility to compaction, for grain of two wheat cultivars - Juma and Maltanka. The results showed that energy requirements at the particular stages of extrusion depend both on the mean particle size and on the wheat cultivar and moisture. It was found out that with an increase in the degree of grain fragmentation and moisture there is a decrease in the work of extrusion and in the value of the index characterizing the susceptibility of the material to compaction. An increase in the mean particle size causes a decrease in the susceptibility of the material to agglomeration.

Keywords: mean particle size, wheat, energy requirements, extrusion

Nomenclature:

$k_i$ - coefficient defining the value of unit total work of compaction related to density increment

$(J \cdot g^{-1}) (g \cdot cm^{-3})^{-1}$

$L_c$ - work of compaction determined till point B on the curve of compaction [J],

$L_c^*$ - total work of compaction determined till point C on the curve of extrusion [J],

$L_c^T$ - unit total work of compaction [J g$^{-1}$],

$L_c^*$ - work of compression (work between points B and C on the curve of extrusion) [J],

$L_c^*$ - work of extrusion (work between points C and D on the curve of extrusion) [J],

$L_c$ - total work of extrusion [J],

$m$ - weight of a sample of the material [g],

$S$ - percentage of work of extrusion relative to the total work of extrusion [%],

$\rho_i$ - material density in the compaction chamber (point C on the curve of compaction) [g \cdot cm$^{-3}$],

$\rho_i$ - initial density of material in the chamber (bulk density) [g \cdot cm$^{-3}$],

INTRODUCTION

In the process of granulation, biological raw materials are subjected to the effect of forces acting between the roller and the die, causing their compaction and the outflow (extrusion) through the forming duct of the die. The effect of various raw materials on that process depends on their physical and chemical properties, and on the adopted process parameters [Hejnl 2002, Kulig et al. 2001, Laskowski et al. 2005]. The properties of raw materials determine the energy requirements of the process, and thus their susceptibility to pelleting. One of the material factors that affect the
energy requirements of pelleting is the degree of fragmentation (particle size of the material). Studies have shown that the best results for pelleting are obtained with materials within the range from 0.4 to 2 mm, i.e. at fine and medium levels of fragmentation [Angulo et al. 1996, Bechke 2001, La Deschault de Monredon 1991, Wondra et al. 1994]. Kulig and Lastowski [2006, 2008], on the basis of research on barley, wheat and lupins, demonstrated that the effect of material particle size on the energy requirements of pelleting depends also on the temperature of the material after its conditioning. They found that the unit requirements of thermal energy, energy of pressing and total energy of pelleting decrease with an increase in the degree of fragmentation of the material. The presented research is concerned with pelleting and permits a general estimation of the energy requirements of the process. Detailed analysis of energy requirements, covering both compaction and extrusion of materials, can be performed in laboratory conditions, in studies on the process of extrusion [Lastowski and Skonecki 2003]. In earlier studies the authors determined the effect of moisture of corn meal, oats and wheat on the process of extrusion [Lastowski and Skonecki 2003], and gave the extrusion process parameters for a number of raw materials and fodder blends [Lastowski et al. 2003].

The objective of the study presented here was determination of the effect of mean particle size (degree of fragmentation) of fragmented wheat grain on energy requirements in the process of extrusion and on the susceptibility of the material to compaction (agglomeration).

MATERIALS AND METHODS

The material used in the study was grain of two wheat cultivars - Juna and Maltanka. The grain was fragmented by means of a HJM/3 beater mill in five different ways - using screens with various mesh sizes and a variant without a screen. For each wheat cultivar five samples of test material were obtained and the mean particle size was determined for every sample. Measurements were made in accordance with the standard PN-89/R-64798 using a laboratory screening set type SZ-1 (the screen set used had mesh sizes of 0.095, 0.18, 0.315, 0.5, 0.8, 1.0, 1.2, 1.6, 2.0 and 3.2 mm, sample weight was 100 g, and screening time was 5 min.). The mean particle sizes for grain samples of wheat cv. Juna were 0.62, 1.11, 1.40, 1.69 and 1.99 mm, and for those of cv. Maltanka - 0.63, 1.05, 1.37, 1.65 and 1.96 mm.

The extrusion process tests were conducted at the temperature of 60°C on samples of wheat grain with moisture levels of 14, 16 and 18% (+/-0.2%). Moisture was determined with the drier method in accordance with the standard PN-76/R-64752.

The extrusion test station included a strength tester type ZD40 [Lastowski et al. 1995, Lastowski and Skonecki 2003] and a pressing assembly with a concentric extrusion aperture with diameter of 6 mm (elastic deformation chamber diameter was 25 mm, piston travel velocity was 0.3 mm/s). All extrusion tests were made in three replications for raw material samples with weight of m=20 g.

In the course of the tests the extrusion characteristics were recorded (Fig. 1) - the relation between force (F) and piston displacement (s). The individual stages of the process of extrusion have been characterized in the work by Lastowski and Skonecki [2001].
The material undergoes compaction until the threshold of outflow (point C). Next, outflow of the material takes place, at decreasing force ($F$), until the threshold of extrusion (point D). The final stage of the process (the so-called phase of ultimate extrusion, $a_4$) covers the outflow of the "dead zone" of the material and from the threshold of extrusion there is an increase in the value of force ($F$) with piston movement ($s$). Recording of that phase is necessary for the determination of parameters for point D.

The curve of extrusion (Fig. 1) was used to determine the energy requirements, i.e.:
- total work of compaction $L_1 (L_1 = L_2 + L_3)$,
- work of extrusion ($L_2$),
- total work of extrusion $L_4 (L_4 = L + L_5)$

Calculation was made of the percentage share of the work of compaction relative to the total work of extrusion $S (S = 100 \cdot \frac{L_1}{L_2})$

The maximum density of material in the chamber was calculated ($\rho_0$), and the unit total work of compaction $L_5 (L_5 = \rho L_1 \cdot m^3$). Those parameters were used to determine the coefficient $k$, characterising the susceptibility of the material to compaction ($k = L_5 \cdot (\rho - \rho_0)$).

For each wheat cultivar determination was made of the relations of the studied features $Y (L_1, L_2, L_3, S$ oraz $k)$ with the mean particle size $d_1$ and moisture $w$, using an equation with the general form of:

$$Y = a + b d_1 + c d_1^2 + d w + e w^2 + f d_1 w$$ (1)

The calculations were made using the SAS Enterprise Guide 3.0 software, determining the significance of coefficients of regression (t-student test) and the significance of the regression equation (adopting a significance level of 0.05). Non-significant variables were eliminated from the equation.
RESULTS

The calculated regression relations are given in Table 1. The data in Table 1 present the significant coefficients of the regression equations and the coefficients of determination $R^2$. The relations of the studied features to the mean particle size $d_i$ for the particular moisture levels are given in Figures 2 - 5.

As follows from the obtained results (Table 1; Fig. 2 - 4), it can be concluded that the character of changes in the work of compaction $L_c$, extrusion $L_e$ and in the total work of extrusion $L_x$ in relation to the mean particle size is similar for the raw materials studied. The work values $L_c$, $L_e$ and $L_x$ increase with an increase in particle size and decrease with an increase in the moisture level of the material. For each degree of fragmentation, the work values were the highest for materials with moisture level of 14%. Higher values of the works were noted for grain of wheat cv. Maltaika.

Table 1. Coefficients of regression equations for the relation of the studied features to mean particle size $d_i$ and moisture content of the material $w$.

<table>
<thead>
<tr>
<th>Wheat variety</th>
<th>Feature</th>
<th>Equation coefficients</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$a$</td>
<td>$b$</td>
</tr>
<tr>
<td>Hordeum</td>
<td>$L_c$</td>
<td>247</td>
<td>458</td>
</tr>
<tr>
<td></td>
<td>$L_e$</td>
<td>-629</td>
<td>1256</td>
</tr>
<tr>
<td></td>
<td>$L_x$</td>
<td>-751.5</td>
<td>821.2</td>
</tr>
<tr>
<td></td>
<td>$k_c$</td>
<td>68.8</td>
<td>541</td>
</tr>
<tr>
<td></td>
<td>$k_e$</td>
<td>-19.8</td>
<td>3.47</td>
</tr>
<tr>
<td>Maltaika</td>
<td>$L_c$</td>
<td>-296</td>
<td>112.4</td>
</tr>
<tr>
<td></td>
<td>$L_e$</td>
<td>133.9</td>
<td>130.1</td>
</tr>
<tr>
<td></td>
<td>$L_x$</td>
<td>1837</td>
<td>511.4</td>
</tr>
<tr>
<td></td>
<td>$k_c$</td>
<td>13.3</td>
<td>-1.064</td>
</tr>
<tr>
<td></td>
<td>$k_e$</td>
<td>-24.5</td>
<td>2.842</td>
</tr>
</tbody>
</table>

The highest work of compaction $L_c = 1941$ (Fig. 2), work of extrusion $L_e = 1252 J$ (Fig. 3) and total work of extrusion $L_x = 1486 J$ (Fig. 4) were obtained for wheat cv. Maltaika with moisture $w = 14\%$ and mean particle size $d_i = 1.96$ mm. The lowest values of those works were obtained for wheat cv. Juna with moisture $w = 18\%$ and particle size $d_i = 0.62$ mm ($L_c = 30 J$, $L_e = 362 J$ (Fig. 3) and $L_x = 392 J$ (Fig. 4)).

Analysing the particular works of extrusion for the given moisture values one can note that with an increase in the mean particle size of the studied wheat cultivars their values increase by 60-90%. As an example, the values of $L_c$, $L_e$, $L_x$ were the highest for wheat cv. Maltaika with moisture of 14%, and for the mean particle size increase within the range from 0.63 to 1.96 mm they were $L_c = 102-1941$, $L_e = 755-1292 J$, $L_x = 837-1486 J$, respectively. Generally, it can be stated that values of the works of compaction and extrusion decrease with an increase in the degree of segmentation of moisture level of wheat grain. The values of the energy requirements of the process of extrusion also depend on the wheat cultivars.
Fig. 2. Relation of the work of compaction $I_c$ to mean particle size $d$ for particular levels of $w$ of wheat cv. Junu and Maltanka.

Fig. 3. Relation of the work of extrusion $I_e$ to mean particle size $d$ for particular levels of $w$ of wheat cv. Junu and Maltanka.

In estimation of energy requirements in extrusion it is important not only to determine the values of work for the particular stages of the process, but also the share of these works relative to
the total work of extrusion. Fig. 5 presents the relations between the share of energy of the phase of extrusion \( S \) and the particle size \( d \), for the wheat cultivars studied. As can be seen in Fig. 5, an increase in the particle size is accompanied by a slight decrease in the work of extrusion \( S \). Therefore, greater work is required for the compression of material before its outflow begins.

**Fig. 4.** Relation of the total work of extrusion \( I \), to mean particle size \( d \), for particular levels of \( w \) of wheat cv. June and Malanka.

**Fig. 5.** Relation of the share of the work of extrusion in the total work of extrusion \( S \) to mean particle size \( d \), for particular levels of \( w \) of wheat cv. June and Malanka.
A notable effect of moisture on the share of the work of extrusion is observed. High values of $S$, within the range of 90-92%, were obtained for raw materials with moisture level of 13%. Decrease in the moisture content to 14% caused a decrease in the value of $S$ to approx. 87%. Therefore, raw materials with lower moisture require more energy for compaction, which may be attributed to increased friction and drag till the outflow of the material.

Energy requirements for compaction indicate the susceptibility of materials to compaction (agglomeration). This information is provided by the value of coefficient $k_c$ defined as the unit work of compaction related to density increment. The lower the value of that coefficient, the higher the capacity of a material for agglomeration. Changes in the coefficient $k_c$ relative to the mean particle size and moisture (Table 1; Fig. 6) are similar to changes in the work of compaction.

![Graph showing the relation of $k_c$ to mean particle size for different levels of moisture in Juna and Malanka.](image)

Fig. 6. Relation of the value of coefficient $k_c$ to mean particle size $d_{50}$ for particular levels of moisture (w%) of wheat cv. Juna and Malanka.

Coefficient $k_c$ increases with an increase in the mean particle diameter and decreases with an increase in moisture level of the wheat cultivars under study. The values of the coefficient were the highest for wheat cv. Malanka with moisture of 14% (from 7.17 to 12.78 (J.g$^{-1}$)(g.cm$^{-3}$)$^{-1}$). For the same material, but with moisture of w=15%, the value of coefficient $k_c$ increased with an increase in the mean particle size, from 3.25 to 6.98 (J.g$^{-1}$)(g.cm$^{-3}$)$^{-1}$. The lowest values of $k_c$ were obtained for wheat cv. Juna with moisture of 15% (from 2.19 to 3.32 (J.g$^{-1}$)(g.cm$^{-3}$)$^{-1}$). As shown by the tests, materials with greater degree of fragmentation have better agglomeration capacity. The results of this study support the relations obtained in the study on the process of agglomeration of cereal meals [Kulig et al. 2001].

CONCLUSIONS

1. Energy requirements in the process of extrusion depend on the mean particle diameter, moisture, and wheat cultivars.
2. Values of energy in the phases of compaction and extrusion were the highest for materials with the largest particle size and the lowest moisture content of the materials.

3. The share of the work of compaction was found to increase with an increase in the degree of fragmentation and moisture of the material. Greater amounts of energy are required in the case of materials with lower moisture and larger mean particle diameters.

4. An increase in the mean particle diameter causes a decrease in the agglomeration capacity of the material.

REFERENCES


Wpływ wielkości cząstek rozdrobnionej pszenicy na nakłady energii w procesie wytłaczania

Streszczenie: Przedstawiono wyniki badań nad określением wpływu średniego wymiaru cząstek na nakłady energii w procesie wytłaczania oraz na waleczek polaności materiału na zagęszczenie rozdrobnionych zasobów odmian pszenicy lana i Malta. Wyniki wykazały, że nakłady energii postępowych na wytłaczanie zależą zarówno od średniego wymiaru cząstek, wilgotności jak i odmiany pszenicy. Stwierdzono, że zwiększenie średniego wymiaru cząstek i wilgotności ma wpływ na wzrost nakładów energii wytłaczania oraz współczynnik omawiany charakteryzujący polaność materiału na zagęszczone. Zwiększenie średniego wymiaru cząstek powoduje zmniejszenie polaności materiału na zawilgocanie.

Słowa kluczowe: średni wymiar cząstek, polaność, nakłady energii, wytłaczanie