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MODELING OF THE PROCESS OF IMPACT-RESISTANT GRAIN MATERIALS' SHREDDING

Summary

Within the framework of the study's realization, an attempt was taken up aiming at modeling of the impact-resistant process of grain materials' shredding with the use of the shredder beater. There was presented a model describing the required speed of a working assembly together with beaters, in order to maintain the technological grain's partitioning. Such a model considers the grain's dimensions and its physiomechanical properties.
***Key words**: Impact-resistant process, modeling of the shredding process, grain material*

MODELOWANIE PROCESU UDARNOŚCIOWEGO ROZDRABNIANIA MATERIAŁÓW ZIARNISTYCH

Streszczenie

W ramach realizacji pracy podjęto próbę modelowania udarnościowego procesu rozdrabniania materiałów ziarnistych za pomocą rozdrabniacza bijakowego. Przedstawiono model opisujący wymaganą prędkość zespołu roboczego wraz z bijakami w celu zapewnienia technologicznego podziału ziarna. Model uwzględnia wymiary ziarna oraz jego właściwości fizyko-mechaniczne.
***Słowa kluczowe**: proces udarnościowy, modelowanie procesu rozdrabniania, materiał ziarnisty*

1. Introduction

Shredding of grain material is one of the main technological operations performed in the food-agrarian industry. It consists in the material's partitioning into smaller parts with the use of a machine's operating elements, which overcome the material particles' cohesion forces. While selecting a shredding mode, one should consider the mechanical properties of material to be shredded, selecting such a mode of working elements' interaction which would make it possible to obtain the required degree of grain material's shredding at possibly lowest machine's stresses destructing the shredded material.

The process of material's shredding is considered in terms of the process efficiency, its power consumption, and the degree of particles' shredding.

The below listed types of shredders are at present used among others by the industry:

- roller mills,
- radial plate grinding mills,
- crushing mills,
- beater shredders.

Out of many types of shredders, from the point of the shredding process effectiveness, the beater shredders [2, 4, 7, 9-11] are the most widely used.

2. Analysis of the issues concerning impact-resistant shredding with the use of a beater shredder

The basic elements of the typical beater shredder are: a rotor with self-aligned or rigidly attached beaters, a shredder's sieve, a shredding plate and a supporting structure with a power transmission system. In the beater shredders, the grain material relocates from a charging hopper to the operating area, where there is a rotor with beaters. The supplied material, under the impact of the beaters' hits reaches the speed from the range from 40 to 110 m/s and moves along the circular path hitting against the shredding plates in case of their presence, against the sieve and hitting each other. As a result of the impact-resistant forces' interacting, the shredded material stays in the shredding chamber as long, till it shall reach appropriate geometrical features to get outside the shredding chamber through the openings in the sieves. An exemplary diagram of the operating beater shredder is presented in Fig. 1.

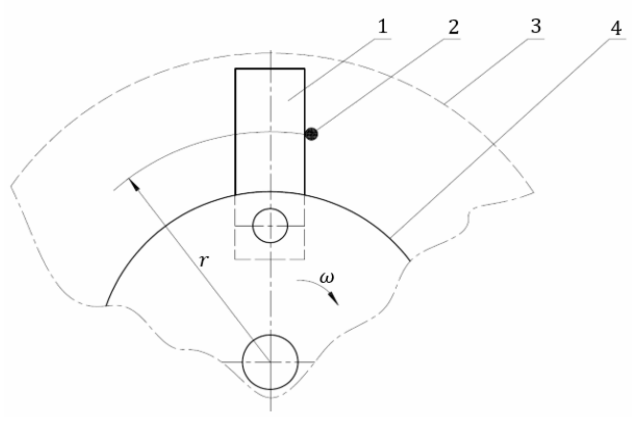

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Fig. 1. Diagram of an operating beater shredder: 1 - beater, 2 - grain element, 3 - sieve, 4 - rotor

Rys. 1. Schemat zespołu roboczego rozdrabniacza bijakowego: 1 - bijak, 2 - element ziarnisty, 3 - sito, 4 - wirnik

The issues of analytical studies relating to gran material's shredding, were presented among others, in the works of: Bond, Brach, Dmitrewski, Flizikowski, Kick, Melnikow, Rittinger and Rebinder [1, 3, 5, 6, 8, 12].

The works conducted on development of the theory of shredding, do not create a uniform presentation of that issue, because of the considered impact of many different factors on the shredding process. The mathematical models presented by the above-named researchers and concerning the shredding theory, described the dependencies relating to energy necessary for the process realization, which was expressed as the energy necessary to overcome the shredded material's cohesion forces, due to what most of the existing hypotheses are of the resistance theory's nature. Based on the mathematical models presented in the available literature, the unambiguous dependencies cannot be derived in order to conduct the analysis of effectiveness in terms of a method and a machine performing that process. It results from different assumptions and simplifications assumed by the researchers.

Studies on the shredding process modeling, the impact on the shredders' construction features and the parameters of their work at the time of cereals' grains shredding prove, that one coherent theory expressing exhaustively that process is missing, and the views within the scope of the constructional features and parameters' impact on the functioning effectiveness are divergent. Mathematical models describing the shredding process are in some cases too general, what causes that their use in the phase of designing the machines for grain material's shredding, is impossible.

The quoted examples of analytical and experimental studies prove, that the subject of shredding of material just like cereals' grain, has not still been fully explored. The constructional solutions of the used beater shredders remain unchanged for many years. There are no precise studies concerning the unit energy consumption in the shredding process. In the available temperature it is only mentioned, that the unit energy consumption depends on many constructional factors, that is the rotor's construction, shape of the beaters and the type of the used sieves. In the known publications connected with conducting of research studies, there are presented contradictory opinions as far as the impact of constructional and exploitation factors on the unit energy consumption and the quality of the shredded product are concerned.

3. Modeling of the shredding process

During statical grain's compressing, the work accumulated in one grain may be described with dependency known from the theory of elasticity:

$$L = \frac{\sigma^2}{2E} V, \qquad (1)$$

where:

L - work accumulated in a grain of volume V and Young E module

σ - compressive stress in a grain.

Accepting the dependence (1) in the description of the energy of elasticity accumulated in grain, is connected with grain's replacement with a cylindrical element having the length l and the sectional area F (Fig. 2).

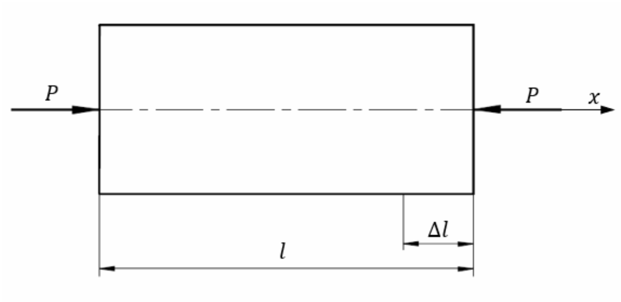

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Fig. 2. Model of grain subject to compression with P force

Rys. 2. Model ziarna poddany ściskaniu siłą P

Compression work L of the cylindrical element on the Δl path may be described with dependence:

$$L = \int_0^{\Delta l} P \, dx, \qquad (2)$$

where:

P - compressing force,

dx - element of the path along which the P force operates

Δl - length described with dependence (3).

Shortening of the cylindrical element for the length Δl may be described as the dependence:

$$\Delta l = \frac{P\,l}{E\,F}, \qquad (3)$$

where:

E - Young module,

F - section area of a cylindrical element,

l - total length of the grain model.

Rearranging the dependence (3), we receive the expression describing the force P in the form:

$$P = \frac{E\,F}{l} \Delta l, \qquad (4)$$

For any dislocation x, the expression (4) takes the following form:

$$P = \frac{E\,F}{l} x, \qquad (5)$$

Presenting the equation (5) to (2) and integrating, we get the dependence describing the operation L of a cylindrical element's compressing:

$$L = \int_0^{\Delta l} \frac{E\,F}{l} x^2 = \frac{E\,F}{2l} \Delta l^2, \qquad (6)$$

Trying to calculate the single grain's compression work, there has been assumed its model composed of a bigger number of cylindrical elements having different diameters (Fig. 3).

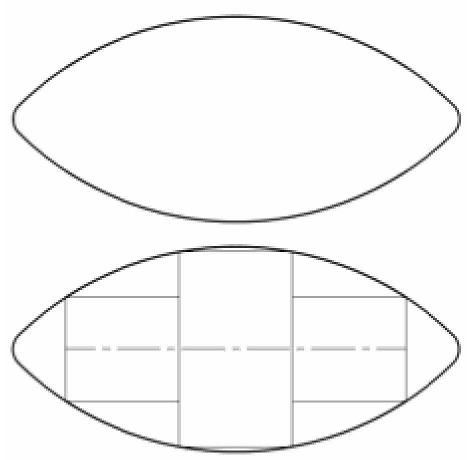

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Fig. 3. Grain's model

Rys. 3. Model ziarna

Discretization is to be conducted maintaining equality of the grain V volume and the sum of cylindrical elements V_m, volume, where:

$$V_m = V_1 + V_2 + V_3 + \dots + V_n.$$

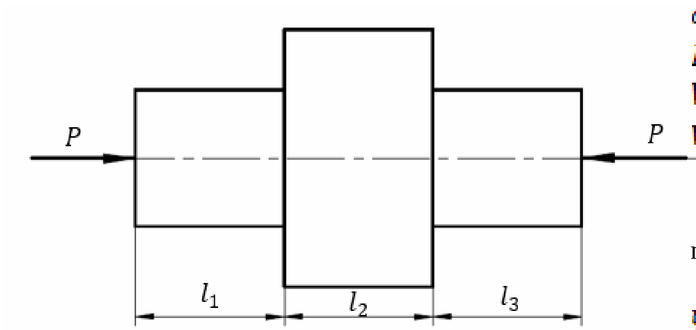

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Fig. 4. Three-element grain's model subject to pressing with P force

Rys. 4. Model trójelementowy ziarna poddany ściskaniu siłą P

In Fig. 4 there is presented the grain's model composed of three cylindrical elements of the lengths $l_1, l_2\ i\ l_3$ and the sectional areas $F_1, F_2\ and\ F_3$. Under the impact of the force P, individual cylindrical elements deform respectively to the lengths $\Delta l_1, \Delta l_2\ and\ \Delta l_3$, where:

$$\Delta l_1 = \frac{P\,l_1}{E\,F_1}, \quad \Delta l_2 = \frac{P\,l_2}{E\,F_2}, \quad \Delta l_3 = \frac{P\,l_3}{E\,F_3}, \qquad (7)$$

The deformation operation L_m of the grain model presented in Fig. 4 is the sum of the deformation operations of its individual elements, pursuant to the dependence:

$$L_m = L_1 + L_2 + L_3. \qquad (8)$$

So, substituting to the dependence (8) the equation (3) there has been received:

$$L_m = \int_0^{\Delta l_1} \frac{E\,F_1}{l_1}\,x\,dx + \int_0^{\Delta l_2} \frac{E\,F_2}{l_2}\,x\,dx + \int_0^{\Delta l_3} \frac{E\,F_3}{l_3}\,x \qquad (9)$$

Following integration of the equation (9), the elasticity energy for the three-element grain's model amounts to:

$$L_m = \frac{1}{2}\frac{\sigma_1^2}{E}V_1^2 + \frac{1}{2}\frac{\sigma_2^2}{E}V_2^2 + \frac{1}{2}\frac{\sigma_3^2}{E}V_3^2, \qquad (10$$

For the purposes of precise grain's mapping, there has to be assumed the mode composed of n cylindrical elements. Then, the dependence (10) takes the form:

$$L_n = \frac{1}{2\,E}\sum_{i=1}^{n} \sigma_i^2\,V_i^2. \qquad (11)$$

The grain is shredded when stress σ reaches the critical value σ_k. For the one-element model, the value of the critical operation L_k, at which shredding of the grain shall take place in accordance with the equation (1) takes the form:

$$L_k = \frac{\sigma_k^2}{2\,E}\,V, \qquad (12)$$

Considering the multi-element model, it has to be assumed that shredding of grain shall take place when the highest stress σ_i reaches the value σ_k. The dependence (11) for critical operation takes the form:

$$L_{nk} = \frac{\sigma_k^2}{2\,E}\,V \sum_{i=1}^{n} \frac{\sigma_i^2}{\sigma_k^2}\frac{V_i}{V}. \qquad (13)$$

where:

σ_i - compressive stress in x element of the model,

σ_k - critical value of the compressive stress,

E - Young model of grain,

V_i - volume of x a model's element,

V - total volume of a model's element.

For further analysis, there has been introduced the dimensionless function ψ described with dependence (14):

$$\psi = \sum_{i=1}^{n} \frac{\sigma_i^2}{\sigma_k^2}\frac{V_i}{V}, \qquad (14)$$

which for the one-element model assumes the value $\psi = 1$.

The critical operation of the one-element model may be presented in the form:

$$L_{nk} = \psi\,\frac{\sigma_k^2}{2\,E}\,V = \psi\,\frac{\sigma_k^2}{2\,E}\,\frac{m}{\varrho}, \qquad (15)$$

where:

ψ - dimensionless function described with dependence (14),

m - mass of grain,

ϱ - thickness of grain.

The condition of grain's shredding is the fulfillment of inequality:

$$E_k > L_{nk}, \qquad (16)$$

where:

E_k - kinetic grain's energy at the moment of collision with the shredder's beater,

L_{nk} - critical work described with equation (15).

Grain's kinetic energy E_k is described by dependence:

$$E_k = \frac{1}{2}\,m\,v^2 = \frac{1}{2}\,m\,\omega^2 r^2, \qquad (17)$$

where:

m - mass of grain,

v - grain's speed with the reference to the beater,

ω - angular speed of the rotor with beaters,

r - radius of grain's collision with beaters.

Substituting the equation (15) and (17) to inequality (16) we shall receive the dependence (18) describing the rotor's speed with beaters has been reached. The condition of grain's shredding there shall be ensuring in the shredding process of the beaters' angular speed, meeting the inequality (18)

$$\omega > \frac{\sigma_k}{r}\sqrt{\frac{\psi}{E\,\varrho}}. \qquad (18)$$

4. Summary

Searching for a mathematical model which would make it possible to describe the design features of the working assembly and the physio-mechanical features of the grain material influencing the shredding process energy consumption in the most similar way, constitutes an important research problem. There has also been conducted an analysis of the so-far known shredding theories which, in many cases assume a too general form, what results in the fact, that their application at the phase of grain materials shredding machines' designing is simply impossible.

From the model presented in the study it results, that determining the shredding assembly's operating speed shall be possible due to the type of shredded material and its physiomechanical properties. Use of that model may reduce the energy losses resulting from incorrect selection of the shredding speed (speed taking too high values) and losses connected with the grain material's damaging (too low speed values – no technological grain's partitioning).

5. References

[1] Bochat A., Wesołowski L.: Nowa konstrukcja zespołu roboczego rozdrabniacza bijakowego. Inż. Ap. Chem., 2009, 48, 2, 25-26.

[2] Bochat A., Wesołowski L.: Analiza rozwiązań konstrukcyjnych rozdrabniaczy bijakowych w aspekcie efektywności ich funkcjonowania. Inż. Ap. Chem., 2010, 49, 5, 22-23.

[3] Bochat A., Wesołowski L., Zastempowski M.: Tests of the innovative construction of the grain hammer mill. Journal of Research and Applications in Agricultural Engineering, 2017, Vol. 62(1), 15-20.

[4] Chwiej M.: Opracowanie analityczne elementów roboczych rozdrabniarki bijakowej w aspekcie wydajności i zużycia energii. Roczniki Nauk Rolniczych, 1986, 76.

[5] Flizikowski J., Sadkiewicz J., Tomporowski A.: Charakterystyki użytkowe sześciowalcowego mielenia uziarnionych surowców dla przemysłu chemicznego i spożywczego. Przemysł Chemiczny, 2015, 94, 1, 69-75

[6] Flizikowski J.: New theory of micro- and nano-grinding. Ekologia i Technika, 2018, 148, 1, 48-56.

[7] Flizikowski J., Mroziński A., Tomporowski A., Jankowski M.: Stanowisko monitorowania charakterystyk użytkowych rozdrabniania. Technika Transportu Szynowego, 2013, 10, 2009-2022.

[8] Kapur P.C., Schoenert K., Furstenau D.W.: Energy-size relationship for breakage of single particles inarigidly mounted roll mill. International Journal of Mineral Processing, 1990, 29.

[9] Opielak M., Komsta H.: Kierunki badań procesu rozdrabniania sypkich materiałów rolno-spożywczych. Zeszyty Naukowe Politechniki Opolskiej, 2000.

[10] Tomporowski A., Flizikowski J., Kruszelnicka W.: A new concept of roller-plate mills. Przemysl Chemiczny, 2017, 96(8), 1750-1755.

[11] Tomporowski A., Flizikowski J.: Motion characteristics of a multi-disc grinder of biomass grain. Przemysl Chemiczny, 2013, 92(4), 498-503.

[12] Wesołowski L., Bochat A.: Próba modelowania bijakowego rozdrabniania materiałów ziarnistych. Inż. Ap. Chem., 2010, 49, 5, 127-129.

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