DETERMINATION OF OPTIMUM APEX ANGLE OF CONE-SHAPED PART OF MATRIX HOLE OF PELLETIZER BY MEANS OF SIMULATING BIOMASS GRANULATION PROCESS

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Abstract. The disadvantage of granulated biofuel is high energy costs of production. The costs can be reduced by optimizing the matrix design including the measure of the apex angle of the cone-shaped part of the matrix hole die. An analytical model of the first phase of the process of granule formation has been developed. The roller creates a pressure P_{pr}, part of the compacted biomass is pressed through and a pellet begins to form. Simulation was conducted for pellet diameters of 6 mm and 8 mm at the expansion coefficient of compacted material after leaving the die being c = 1.017. The die length during modelling was assumed to be within the limits of 10-110 mm at a pitch of 20 mm. The height of a raw material layer taken in by a roller during pressing, was within the limits of 1-7 mm. The significance of function determination coefficients $P_{pr} = f(2\gamma)$ and $2\gamma_{opt} = f(h_{pr})$ was tested according to Fisher's ratio test, the significance of function coefficients $P_{pr} = f(2\gamma)$ and $2\gamma_{opt} = f(h_{pr})$ was determined according to Student's test. The dependence of $P_{pr} = f(2\gamma)$ on the extremum $P_{pr} \rightarrow$min by the dichotomy method has been determined and verified by the modeling method. Functional dependence of the apex angle of the cone-shaped part of the pelletizer die on the height of a raw material layer, which is taken in by a roller during pressing has been determined. To justify the rational angle of the inlet cone-shaped part of the die, a mathematical model of the process was developed. Under the condition of pressure reduction, the optimum apex angle of the cone-shaped part of the granulator die is equal to 26° at h_{pr} = 1 mm, 32° at h_{pr} = 2 mm, 41° at h_{pr} = 3 mm, 59° at h_{pr} = 4 mm, 109° at h_{pr} = 5 mm, 122° at h_{pr} = 6 mm, 131° at h_{pr} = 7 mm and it is approximated with the accepted coefficient of determination by Newton quartic polynomial, which makes it possible to determine the design and process parameters of the granulation unit under the condition of the minimum energy cost of pressing.

Keywords: granules, matrix, cone die, rollers, modeling.

Introduction

The most efficient way of biomass preparation for its further utilization as a fuel source is its granulation, since the final moisture content of the finished product is equal to only 8-12% and the raw material is compacted 5-10 times, which reduces transportation costs. Granulated fuel has a number of other advantages including constancy of qualitative variables, convenience of storage and transportation, applicability in self-feeding heating systems. It is a clean fuel as any other biofuel. As a rule, in order to produce fuel pellets, valuable industrial raw material is not used. Instead, forest product and agriculture residues are widely applied [1; 2]. The key disadvantage of granulated biofuel is high energy costs of its production. Together with substantial capital equipment expenditures it defines its high cost. It is possible to reduce energy costs during fuel pellet production by means of optimizing the design and process parameters of the matrix. These parameters include the measure of the apex angle of the cone-shaped part of the matrix die [3; 4].

Materials and methods

Survey of the mathematical models of biomass granulation process. Material compacting during its granulation is performed by means of pressing, which is approximation and adhesion of solid-phase particles, that is to say, compacting and stabilization of loose biomass by means of mechanical pressing. During pressing, the following processes take place: material takes high pressure from a press; friction between particles as well as friction between particles and the press result in the increased temperature; a cell structure is ruined due to high temperature and pressure; heating results in biomass lignin softening and it glues the compacted particles [5; 6]. Every time a roller passes over the inlet opening of a matrix die, a part of compacted biomass from the pressed raw material layer is forced through the die under the action of roller pressing pressure P_{pr} (Fig. 1).

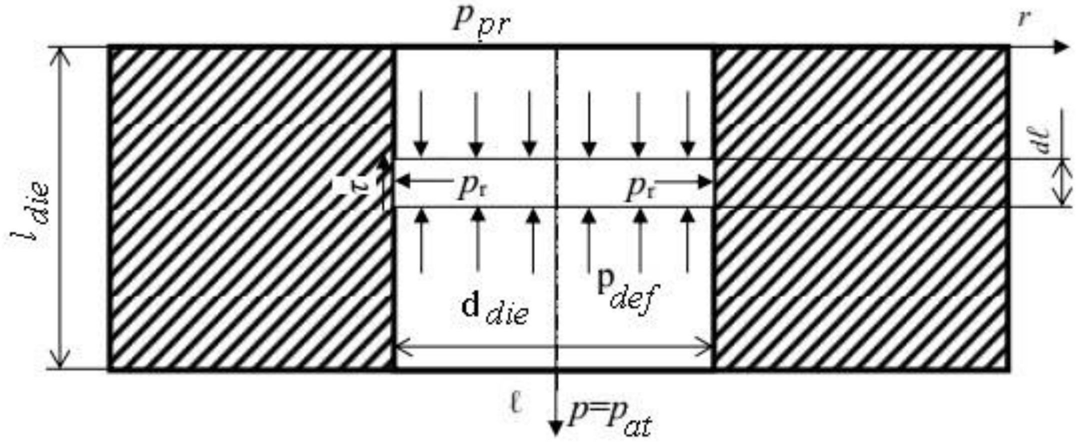

Fig. 1. **Scheme for determining pressing force in a matrix die [7]**

Due to the elastic deformation force (P_{def}) of a pellet as well as friction forces (friction induced shear stress τ) and normal stress (P_r), which act on the side cylindrical surface of a distinguished element, compacted raw material mass forced in a die (e.g. infinitely small cylindrical granular element being d_{die} in diameter and dl thick) creates a backpressure for the roller pressing pressure force; thus, every roller passing results in the increase of pressing pressure and compacted mass pushing force and, hence, particle density increases as well. This lasts until the pressure of raw material layer pressing and the pressure of forming and pushing a finished pellet through a die become equal; afterwards, a stationary working mode of a pelleting-press is achieved [8; 9].

The paper [10] states that a die of a smaller diameter provides higher pellet density. The dependence of the dynamic friction coefficient on pelleting speed has been determined. In addition, it has been found that the dynamic friction coefficient is directly related to the angle of friction surface inclination. The paper [11] covers research on determining the gripping angle of a roller. The lowest energy costs and the highest pelleting speed have been observed at the inclination angle of β = 45° and roller diameter-vs-die diameter relation being 0.585 [12].

Pressing pressure is one of the key parameters of compacting. The density of the produced pellets, the design and energy parameters of a pelleting-press depend on its value. Professor S. Melnikov deduced the main equation of pressing granular and fibrous capillary-porous materials, which determined the unique dependence of the pressing pressure on the density of the obtained pellet monolith [7]:

$$P_{pr} = C \cdot \left(e^{a \cdot (\rho_{gr} - \rho_{raw})} - 1\right), \tag{1}$$

where P_{pr} – pressing pressure, MPa;

ρ_{gr}, ρ_{raw} – density of pellets and raw material, respectively, kg·m^{-3};

a and C – experimentally determined parameters, which depend on material structural and mechanical properties (strength, moisture content, particle size) and define material compressive strength ability, m^3·kg^{-1} and MPa, respectively;

e – Euler number, the basis of natural logarithm.

Z. Kuchinkas et al. note that the basic pressing equation was derived assuming that pressing force does not depend on the rate of deformation. This assumption is true for the deformations that progress slower than stress relaxation does. If deformation progresses faster than stress relaxation does, compressive strength depends on the rate of deformation as well. Here, the pressing pressure is determined according to the following formula [9; 13; 14]:

$$P_{pr} = C \cdot \left(1 + 0.173 \cdot v_{pr}\right) \cdot \left(e^{a \cdot (\rho_{gr} - \rho_{raw})} - 1\right), \tag{2}$$

where v_{pr} – pressing speed, m·s^{-1}.

The above-mentioned expressions make it possible to determine the pressing pressure only if the values of the experimentally determined parameters a and C are known. At the same time, the values of the parameters *a* and *C* for wood raw materials have not been reported. The model of the granulation process is presented in the paper. However, according to the expressions (1) and (2), the dependence of the pressing pressure on the pellet length is of exponential character, which contradicts the results of the experimental studies that describe it by a linear function [7].

Popov considered the pressing process as follows. When a pressing roller 3 passes above the cone-shaped part of the die 2, the cutting of biomass out of the layer 5 takes place and it is further pressed in the layer 4, while biomass from the layer 4 is pressed in a conic hole and then in the cylindrical passage of the die 1 (Fig. 2).

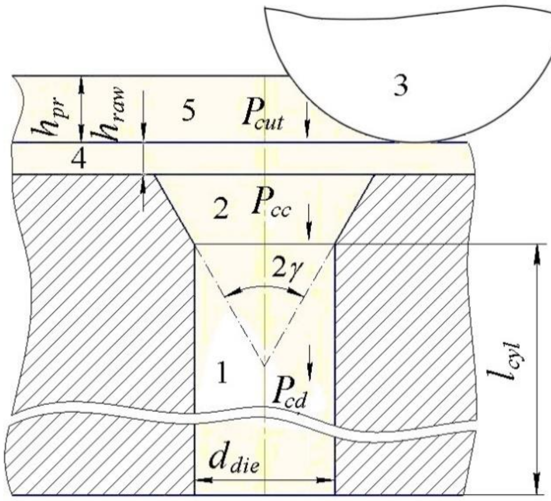

Fig. 2. **Diagram of biomass pressing in a matrix die**

With every new passing of the pressing roller, compacted biomass is forced deeper along the cylindrical part of the die experiencing greater compaction. Thus, A. Popov suggested determining the pressing pressure as the sum of pressures for cutting wood pulp out of the compacted layer P_{cut}, pressing the cut-out wood pulp through a conic hole into the cylindrical passage of the die P_{cc}, forcing the formed wood pellet through the cylindrical passage of the die P_{cd} [7; 13]:

$$P_{pr} = P_{cur} + P_{cc} + P_{cd} \,. \tag{4}$$

The pressure for cutting wood pulp out of the compacted layer P_{cut} is determined according to the expression [7]:

$$P_{cut} = \sigma_\tau \cdot \frac{4 \cdot h_{\mathrm{lraw\,pr}}}{d_{die} + 2 \cdot l_{\mathrm{cc}} \cdot tg(\gamma)}, \tag{5}$$

where σ_τ – limit of liquidity, MPa;
$h_{lraw\ pr}$ – height of the raw material layer that is taken in by the roller during pressing, m;
d_{die} – die diameter, m;
l_{cc} – length of the cone-shaped die part, m;
γ – half apex angle of the cone-shaped die part, deg.

Pressure in the conical passage of the die P_{cc} is determined according to the expression [14]:

$$P_{cc} = 2 \cdot \left(1 + \frac{f \cdot \nu}{2 \cdot \left(1 - \cos(\gamma) + \sin^2(\gamma)\right)}\right) \cdot \sigma_\tau \cdot \ln \frac{d_{\mathrm{gr}}}{d_{\mathrm{die}}}, \tag{6}$$

where f – friction coefficient;
ν – Poisson ratio;
d_{gr}, d_{die} – pellet diameter and die diameter, respectively, m.

Pressure in the cylindrical passage of the die P_{cd} is determined according to the expression [7; 14]:

$$P_{cd} = 4 \cdot \frac{f \cdot l_{cd}}{d_{die}} \cdot \frac{E}{1+\nu} \cdot \frac{\left(d_{gr} - d_{die}\right) \cdot \left(\frac{d_{gr}^2}{d_{die}^2} - 1\right)}{d_{\phi} \cdot \left(1 - 2 \cdot \nu + \frac{d_{gr}^2}{d_{die}^2}\right)}, \quad (7)$$

where E – Young's modulus, MPa.

Literature data analysis did not make it possible to determine the optimum measure of the apex angle of the cone-shaped die part under the condition of minimum energy cost of the pelletizing process. Thus, the research is aimed at determining the optimum apex angle of the cone-shaped part of a granulator die under the condition of minimum energy cost of the pelletizing process by means of simulating the process of biomass granulation.

The dependence $P_{pr} = f(2\gamma)$ was determined by means of simulating the process of biomass granulation; it was tested for the extremum $P_{pr} \rightarrow \min$ using the dichotomy method. Functional dependence of the apex angle of the cone-shaped part of the granulator die on the height of the raw material layer that is taken in by the roller during pressing was determined [7; 15].

Simulation was conducted for pellet diameters of 6 mm and 8 mm at the expansion coefficient of compacted material after leaving the die being c = 1.017. Matrix thickness (die length) during modelling was assumed to be within the limits of 10-110 mm at a pitch of 20 mm, the height of the raw material layer, when it is taken in by the roller during pressing, was within the limits of 1-7 mm at a pitch of 2 mm [16; 17].

The significance of function determination coefficients $P_{pr} = f(2\gamma)$ and $2\gamma_{opt} = f(h_{pr})$ was tested according to Fisher's ratio test, the significance of function coefficients $P_{pr} = f(2\gamma)$ and $2\gamma_{opt} = f(h_{pr})$ was determined according to Student's test.

Results of research

Fig. 3 presents the function $P_{pr} = f(2\gamma)$ for d_{die} = 6 mm and l_{cyl} = 70 mm. For other values of d_{die} and l_{cyl} the value of P_{pr} changes (with the increase of d_{die} and l_{cyl} it increases) but the slope of the curves $P_{pr} = f(2\gamma)$ remains invariant.

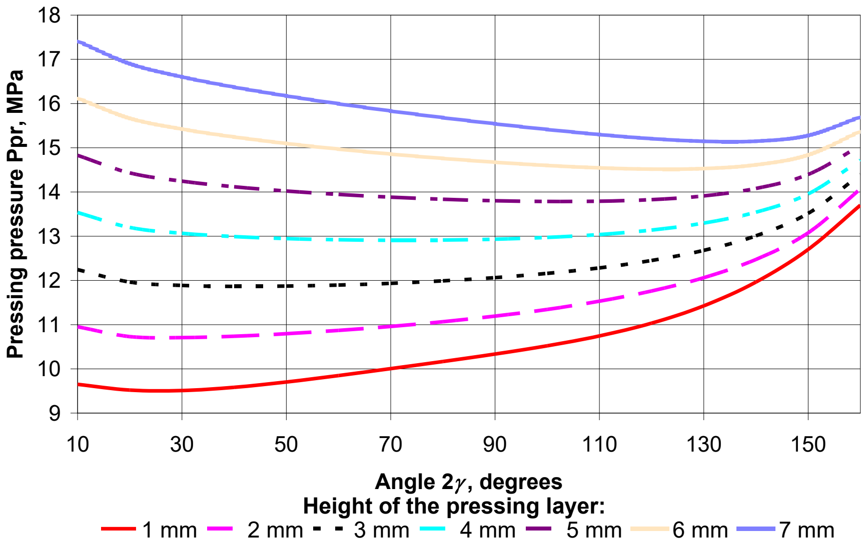

Fig. 3. **Dependence $P_{pr} = f(2\gamma)$ for d_{die} = 6 mm and l_{cyl} = 70 mm**

The function $P_{pr} = f(2\gamma)$ is approximated by Newton quartic polynomial:

$$P_{np} = b_4 \cdot (2\gamma)^4 + b_3 \cdot (2\gamma)^3 + b_2 \cdot (2\gamma)^2 + b_1 \cdot (2\gamma) + b_0, \quad (8)$$

where b_0, b_1, b_2, b_3, b_4 – polynomial coefficients.

Table 1 presents the values of polynomial coefficients (8).

Table 1

Polynomial coefficient values

h_{pr}, mm	b_4	b_3	b_2	b_1	b_0	R^2
1	$3.560 \cdot 10^{-8}$	$-1.029 \cdot 10^{-5}$	0.001134	-0.04039	9.95	0.9995
2	$3.466 \cdot 10^{-8}$	$-1.019 \cdot 10^{-5}$	0.001137	-0.04617	11.30	0.9990
3	$3.372 \cdot 10^{-8}$	$-1.008 \cdot 10^{-5}$	0.00114	-0.05194	12.65	0.9984
4	$3.278 \cdot 10^{-8}$	$-9.968 \cdot 10^{-6}$	0.001143	-0.05771	14.00	0.9971
5	$3.185 \cdot 10^{-8}$	$-9.860 \cdot 10^{-6}$	0.001146	-0.06348	15.35	0.9953
6	$3.091 \cdot 10^{-8}$	$-9.751 \cdot 10^{-6}$	0.001149	-0.06926	16.70	0.9968
7	$2.997 \cdot 10^{-8}$	$-9.643 \cdot 10^{-6}$	0.001152	-0.07503	18.05	0.9985

The determination coefficients of the regression equation (8), which were determined according to [18], show that the obtained regression equation provides reasonably accurate representation of the P_{pr} value, which was obtained from the expression (8). Having performed Fisher's ratio test, the significance of the determination coefficients was found. The performed Student's test [18] showed that all the regression equation coefficients (8) were significant.

The function $P_{pr} = f(2\gamma)$ was tested for the extremum $P_{pr} \rightarrow \min$ using the dichotomy method. The optimum measure of the angle 2γ under the condition of P_{pr}, reduction was determined to be equal to 26° at $h_{pr} = 1$ mm, 32° at $h_{pr} = 2$ mm, 41° at $h_{pr} = 3$ mm, 59° at $h_{pr} = 4$ mm, 109° at $h_{pr} = 5$ mm, 122° at $h_{pr} = 6$ mm, 131° at $h_{pr} = 7$ mm and was approximated according to the expression:

$$2\gamma_{opt} = -0.15 \cdot h_{pr}^4 + 1.75 \cdot h_{pr}^3 - 3.56 \cdot h_{pr}^2 + 6.6 \cdot h_{pr} + 25.8 \text{ at } R^2 = 0.9915, \quad (9)$$

where $2\gamma_{opt}$ – optimum apex angle of the cone-shaped part of the die under the condition of minimum energy costs, deg.;

h_{pr} – height of the raw material layer, which is taken in by the roller during pressing, mm.

Graphic representation of the dependence $2\gamma_{opt} = f(h_{pr})$ is provided in Fig. 4.

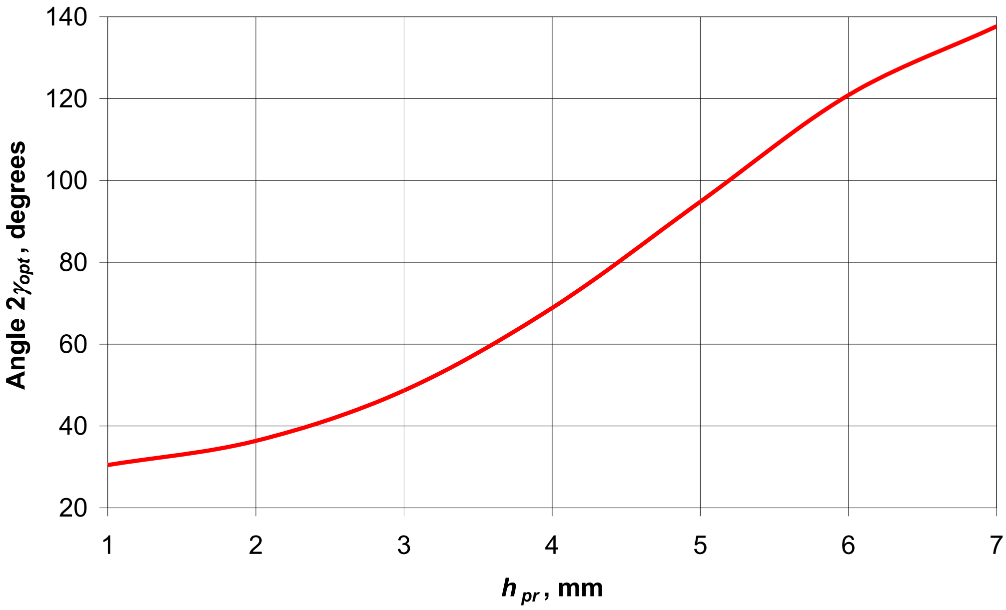

Fig. 4. **Graphic representation of the dependence $2\gamma_{opt} = f(h_{pr})$**

Since the determination coefficient of the approximated function (9), which was determined according to [18], approaches the unity, the value of the function (9) provides reasonably accurate representation of the design data. The significance of the determination coefficient was determined by Fisher's ration test. According to Student's test [18], all the function (9) coefficients are significant.

The function (9) makes it possible to determine the design and process parameters of the granulation unit under the condition of the minimum energy cost of pressing.

Thus, the design and process parameters of the granulation unit of the pelletizer used for producing wood pellets made of woodworking and cabinet-making residues with the capacity of 500 kg·h^{-1} for a privately-owned enterprise called Malynska Furniture Factory were substantiated according to the developed technique [17; 19] applying the dependence $P_{pr} = f(2\gamma)$, which was obtained from the conducted mathematical simulation, and the measured bulk density of the raw material used for producing fuel pellets (149.1 kg·m^{-3}). The granulation unit consists of a ring die with its internal diameter being 300 mm and one roller 166 mm in diameter. The matrix contains 1342 cylinder dies 5.9 mm in diameter with cone-shaped tops 7.73 mm in diameter, which are arranged in 11 rows, 122 dies in one row. The length of a die is equal to 45 mm, the apex angle of the cone-shaped die part is 47°. The diameter of the produced fuel pellets is equal to 6 mm. The working width of the roller and the matrix is 83 mm, the frequency of matrix rotation is 250 rev·m^{-1}, the granulator drive power should be not less than 24 kW, taking into account roller slipping.

Conclusions

The key disadvantage of pelletized biofuel is the high energy cost of its production. It is possible to reduce the energy cost of pellet production by means of optimizing the design and process parameters of a matrix, which includes the apex angle of the cone-shaped part of the granulator die. Under the condition of pressure reduction, the optimum apex angle of the cone-shaped part of the granulator die is equal to 26° at h_{pr} = 1 mm, 32° at h_{pr} = 2 mm, 41° at h_{pr} = 3 mm, 59° at h_{pr} = 4 mm, 109° at h_{pr} = 5 mm, 122° at h_{pr} = 6 mm, 131° at h_{pr} = 7 mm and it is approximated with the accepted coefficient of determination by Newton quartic polynomial, which makes it possible to determine the design and process parameters of the granulation unit under the condition of the minimum energy cost of pressing.

Author contributions

All authors have contributed equally to the study and preparation of this publication. The authors have read and agreed to the published version of the manuscript.

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