IMPROVEMENT OF BIOMASS GRANULATOR MATRIX MECHANISM

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Abstract. Matrix-type granulators have a pressing mechanism consisting of a perforated ring die and rollers that press biomass into the die channels (dies). At high pressures of 40-90 MPa, molecular adhesion (dry extrusion process) occurs between biomass particles in the channels, and intense friction of the material against the walls occurs, which increases the temperature of the pellets to 80-105°C. During operation of the mechanism, technological violations of the “roller-biomass-matrix” system occur in the form of jamming (non-passage) of the material through the matrix channels. This reduces the productivity and reliability of the granulator. A significant disadvantage of the process is the uniform pressure of the rollers on the biomass. Therefore, the biomass is slowly pushed through the channels, creating increased resistance. The purpose of this work is to improve the efficiency of the granulation process by introducing vibrational movements during the rotation of the pressing rollers. This contributes to oscillatory roller pressure, reduces the load on the die, and ensures a more uniform distribution of biomass before entering the die channels. The mechanism includes a matrix and a supporting lever on which the rollers are mounted. The gap between the rollers and the matrix is adjustable in the range of 0.2-0.5 mm. An additional steel sector is installed on the inner wall of the rollers. The geometric parameters of the sector are determined according to a certain method. The pulsating action of the rollers with shifted centres of mass is damped by the damper units in the design of the supporting lever. The rollers with the shifted centre of mass perform vibratory movements during rotation, due to which the pressure on the biomass continuously changes, i.e. pulsates. This increases the efficiency of pushing the biomass through the dies and prevents disruptions to the technological process in the form of biomass jamming. The improved matrix mechanism reduces energy consumption for the drive by 1.2-1.4 times, increases the productivity of the granulator by 9-14% due to the active action of the rollers, and evenly distributes the biomass before it enters the channels of the matrix.

Keywords: pellets, matrix, rollers, mechanism, improvement.

Introduction

One of the key challenges of modern energy systems involves transition to renewable energy sources and making optimal use of agricultural waste. In this context, there is growing interest in the adoption of solid biofuels, particularly pellets made from plant biomass, which help enhance energy independence and environmental safety [1-7]. The matrix-roller mechanism of the granulator plays a decisive role in forming these pellets, as it provides the necessary pressure and shape stability required for transportation and storage [3; 6].

However, traditional granulator designs exhibit several significant shortcomings. The uniform pressure exerted by the press rollers causes slow biomass feeding, creating increased risk of biomass jamming in the matrix channels, reducing productivity, and leading to excessive energy consumption. The uniqueness (newness) of the proposed upgraded matrix-roller assembly lies in the use of rollers with off-centre masses and damper units, which enable pulsating pressure on the raw material. This approach intensifies the compaction process, improves relaxation conditions, and eliminates the possibility of matrix channel blockages.

In this study, we carried out a comparative analysis of standard and modernized biomass pelletizing units by an experimental method. The obtained indicators show an increase in the reliability of the process and the productivity of the granulator due to the vibration (oscillating) movements of the rollers during rotation. The modernized mechanism also facilitates the production of pellets with stable shape and strength, which is crucial for various sectors ranging from agriculture to municipal heating systems.

Materials and methods

Biofuel pellets are formed by forcing raw material through radial matrix channels (dies). They have a cylindrical shape and a uniform diameter, while the granulation process itself corresponds to dry extrusion [1; 2]. The biomass must be rheological continuous to ensure relaxation after pressure release, and the pellets must be sufficiently strong for transportation and storage [3].

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During granulation, the rollers generate contact stress, compacting the biomass and pushing it through the technological channels under a pressure of up to 90 MPa [2; 5; 6]. The biomass is captured by the roller at point A (see Fig. 1), compressed between the working surfaces, and formed into a monolith with a density of 0.3-0.5 $t \cdot m^{-3}$ [5; 6]. At point D, the maximum pressure of 30-90 MPa is reached, ensuring effective extrusion into the channel. Elastic expansion of the biomass layer occurs after exiting the gap between the roller and the matrix, with contact ending at point G [6]. The resultant force of compression and extrusion pressures deviates by 10-15°, determining the position of point D [5; 6].

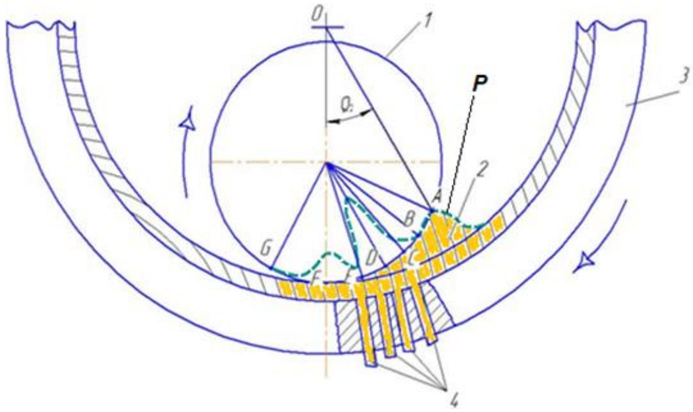

Fig. 1. **Diagram of normal pressures in the compression zone:**
P – normal pressure; 1 – roller; 2 – biomass; 3 – matrix; 4 – pellets

The described phenomena indicate the complexity and heterogeneity (stochastic nature) of the granulation process at its initial stage within the matrix. To enhance the granulation efficiency, it is advisable to develop a structural solution that incorporates additional vibrational movements of the working element – roller 1 (see Fig. 1). This objective is the focus of the present study.

This research on biomass granulation processes is based on the following mechanical and mathematical methods [6; 8-10]: analysis and synthesis of press granulator operating processes; physical modelling considering the natural properties of biomass; and mathematical modelling of the “biomass-roller-matrix-pellet” chain function. The methodology for determining the structural and technological parameters of biomass granulation is based on physical and mechanical modelling of the granulation process for biomass. The technical features of the granulator and the rheological properties of the biomass were taken into account [10; 11]. The authors conducted exploratory and analytical studies to establish quantitative dependencies that mathematically reflect the physical phenomena accompanying the granulation process [6; 11-13]. Energy consumption measurements of the matrix mechanism were performed using a three-phase digital multifunction DIN-rail-mounted meter Voltronic (YT36692). The system employed an electrical measurement approach for non-electrical quantities, converting physically diverse measured parameters into uniform electrical signals [12; 15; 16]. This enabled remote control compliant with ISO 50001, synchronization of parameter measurements with an accuracy of 0.05, and monitoring of their changes. The novelty of the research is explained by the improvement of the design of the pressing roller and its supporting part, which increases the efficiency of the process. The primacy of the technical solution is confirmed by the patent document [14].

Results and discussion

One of the key approaches to the structural modification of the matrix mechanism involves a technical solution where the working surface of the rollers features longitudinal splines. These splines enhance the biomass capture efficiency and ensure more uniform compaction by shifting its layers [6]. This design eliminates the issue of rollers jamming, increases the productivity of the granulation process, and maintains the pellet density.

The subject of this research is the functional structure of the matrix-roller mechanism with technical improvements (Fig. 2). The mechanism consists of a perforated ring-shaped matrix 1 with radial channels 2, driven by a power unit to enable rotational motion [14]. Inside the matrix, pressing rollers 4 are mounted on axes 3, which are fixed to the support lever 6. The support lever is rigidly attached to frame 5, ensuring a working gap of 0.2-0.5 mm between the roller outer surface and the matrix inner surface. Additionally, on the inner wall of the shell 7 of each roller, a steel arc-shaped sector 8 is installed. This sector is positioned along the length of the roller between the bearings 9 (Fig. 3), contributing to the stability and efficiency of the granulation process.

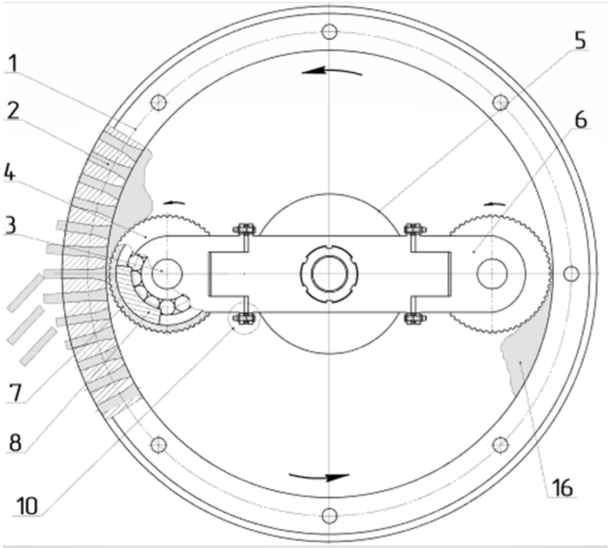

Fig. 2. **Structural and technological diagram of the matrix-roller mechanism:** 1 – matrix; 2 – matrix channel; 3 – axis; 4 – roller; 5 – frame; 6 – lever; 7 – roller shell; 8 – sector; 10 – damper assembly; 16 – biomass

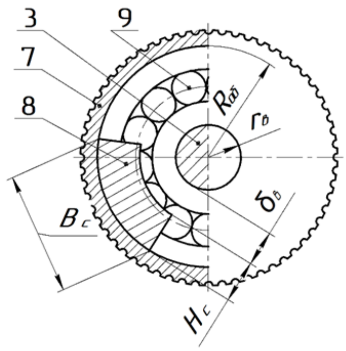

Fig. 3. **Diagram for calculating the parameters of the roller sector:** 3 – axis; 7 – roller shell; 8 – sector; 9 – bearing

The determination of the geometric parameters of the sector was carried out using the (1-3) relations. The length of the sector between the bearings is calculated using the formula:

$$L_{\mathrm{s}} = L_{\mathrm{r}} - 2b_{\mathrm{b}} - 2\delta_{\mathrm{b}}, \tag{1}$$

where L_r – roller length, mm;
b_b – bearing width, mm;
δ_b – technological clearance between the bearing and the sector, mm.

The width of the sector B_s (Fig. 3) is determined by the formula:

$$B_s = (0.3 - 0.4)\pi \cdot R_{rs}, \tag{2}$$

where R_{rs} – inner radius of the roller shell, mm.

The thickness of the sector H_s is calculated as follows:

$$H_s = R_{rs} - (r_a + \delta_a) = R_{rs} - 1.6\, r_a, \tag{3}$$

where r_a – radius of the roller axis, mm;
δ_a – technological clearance between the axis and the sector, mm;
$\delta_a = 0.6\, r_a$.

The damping of pulsating forces exerted by rollers with offset mass centres is achieved through damping units 10 (Fig. 2), which are integrated into the design of the support lever. The technical implementation of the damping system involves dividing the lever along a zigzag-shaped line into three structural components (Fig. 4): two outer sections 11, on which the rollers are mounted, and a central section 12, which is rigidly connected to the frame. To connect these components, brackets 13 are incorporated into the structure of sections 11 and 12. Between these brackets, rubber damping pads 14 are installed. The connecting brackets of section 11 feature threaded holes for bolts 15, while the brackets of section 12 have smooth holes. By utilizing the threads in brackets 13 of section 11, the bolts – secured with locknuts – allow for the adjustment of a technological clearance between the roller and the matrix. During the granulation of biomass 16 (see Fig. 2), the pulsating loads from the roller with an offset mass centre are absorbed by the rubber damping pads 14. Importantly, bolts 15 do not restrict the elastic deformations of the pads, as they can freely move within the smooth holes of the brackets in section 12 [14].

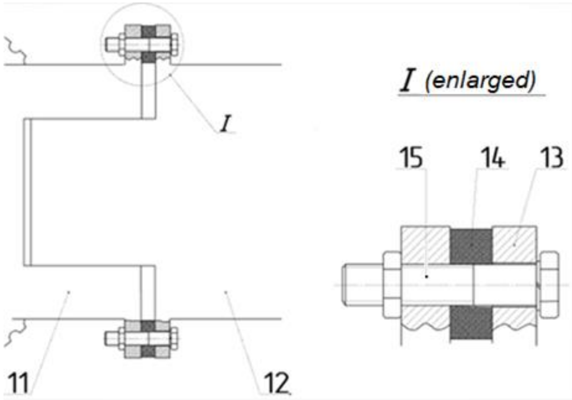

Fig. 4. **Damper units for damping vibrations of press rollers:**
11, 12 – structural components; 13 – bracket; 14 – pads; 15 – bolt

The improved matrix-roller mechanism operates as follows (see Fig. 2). Raw biomass (16) is loaded into the gap between a rotating die and roller, both rotating in the same direction. The roller rotates due to friction within the wedge-shaped gap, compressing the biomass and pushing it through radial channels in the die, forming pellets. Subsequent rollers further compress and push the biomass until pellets exit completely. High pressures and friction heat pellets to approximately 100°C at the exit. Rollers with offset mass centres oscillate during rotation, causing pulsating pressure, thus improving biomass throughput, preventing material jamming, and ensuring continuous operation [14; 16].

The advanced expertise of California Pellet Mill [5; 16] indicates that when the channel diameter ranges from 6 mm to 8 mm, the forming section of the channel should have a length of 40-45 mm. Moreover, pellets with a 6 mm diameter exhibit higher quality compared to those with an 8 mm diameter. Well-known research of conducted pelletizing experiments to determine productivity (Q) of the pressing unit and pellet density (ρ), is considering variables such as the die channel diameter and length, friction coefficient between biomass and the channel surface, roller diameter, and the roller-die gap. The experimental procedure involved single-factor tests with triple repetitions using wood sawdust and sunflower husks. Measurement accuracy was 0.25 m³/h for productivity and 50 kg/m³ for pellet density [9; 10].

The authors applied statistical analysis of experimental data using the computational software "PLAST-GRN". The obtained mathematical relationships and approximation graphs indicate that the die channel length (X_1) and the friction coefficient (X_2) were the most influential factors. Regression equations are presented in expressions 4 and 5 [9; 10].

$$Y_{1(L)} = 0.3012x_1^2 - 29.247x_1 + 1164.3, \quad (4)$$

$$Y_{2(k)} = -205.91x_2^3 + 531.36x_2^2 + 629.09x_2 + 559.53. \quad (5)$$

To verify the efficiency of the modified matrix mechanism, exploratory experiments involving four factors $P = f(L,\ d,\ k,\ u)$ were conducted (Fig. 5) using a GT-305 pelletizer by ICK [3; 6]. The experiment count was determined by a Hartley-Kono $Na4$ experimental design [13]. Pressing pressure was measured indirectly through the energy consumption of the matrix mechanism. Statistical analysis and regression coefficients were computed with STATISTICA software [13]. A triple-replicated experimental approach provided reliability of 0.9 at a permissible fractional error of 1.0. Regression analysis in MS Excel [13] yielded a second-order regression equation (6). Model adequacy was verified using Fisher's test, and the significance of regression coefficients was assessed by Student's t-test [13].

The second-order regression equation describing the change in pressure P, required to push biomass through the die channel, is expressed as follows:

$$P = 0.503 + 63.648X_1^{\,2} - 7.024X_1 + 0.043X_2 + 0.305X_3 + 2.341X_1X_4, \quad (6)$$

where X_1, X_2, X_3, X_4 – coded values of the factors (respectively):
L – length of the matrix channel, mm;
d – diameter of the matrix channel, mm;
k – coefficient of friction between the biomass and the channel surface;
u – technological gap between the roller and the matrix, mm.

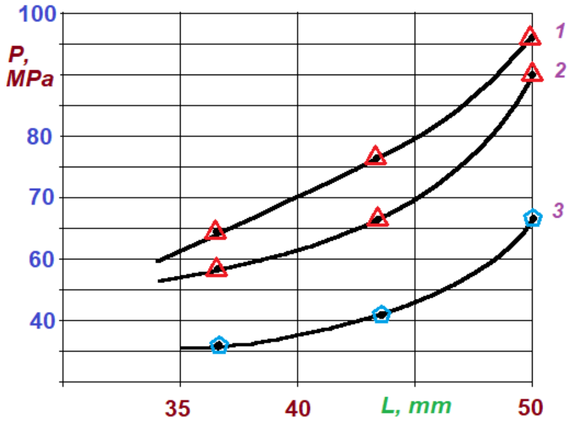

Fig. 5. **Dependence of pressing pressure (P), generated by the roller, on the die channel length (L):** 1 – conventional pressing mechanism (wood sawdust); 2 – conventional pressing mechanism (straw); 3 – modified pressing mechanism (straw)

The enhanced process efficiency is explained by activating the interaction within the “biomass-roller-matrix-pellet” system through vibrations induced by pressing rollers with offset mass centres. Thus, the set objective is achieved through technical and technological modernization of the pressing unit, which contributes to a reduction in the critical pressure between the roller and the matrix when biomass enters the channel (see Fig. 1). Consequently, the reliability and productivity of the process increase by 9-14%. Additionally, due to more uniform filling of the matrix channel and lower entry pressure, conditions are created for utilizing less costly metals in matrix production. This enables an increase in the matrix thickness and correspondingly the pelletizing channel length by 10-12%. For example, the thickness of matrices from California Pellet Mill for pellets with diameters of 6-8 mm has been increased to 50 mm, facilitating a more complete relaxation of internal stresses within pellets as they exit the matrix. As a result, elastic after-effects are minimized, and the quality of the finished pellets improves by two to three levels without a reduction in their density (900-1100 kg·m^{-3}).

Conclusions

1. The modified design of the matrix-roller mechanism for producing biofuel pellets contributes to a reduction in the energy consumption by 1.2-1.4 times per drive while maintaining sufficient pressure for granulation. It enhances the granulator productivity by 9-14% due to the activation effect of the pressing rollers, improves the pellet quality through the uniform distribution of biomass before entering the receiving sections of the matrix channels, and ensures variable pressure due to the pressing rollers with shifted mass centres.
2. The conducted experimental studies confirm the expected efficiency of the modified pressing unit of the granulator. Due to the activation of the process through the vibrational effect of the rollers, biomass is pushed into the matrix channels more intensively. This allows for 10-12% increase in the matrix thickness, from 40-45 mm to 50 mm, while using lower-cost metal. The conditions for relaxation processes significantly improve, leading to an increase in the technological quality of the pellets by two to three levels.

Author contributions

Conceptualization, O.Y.; methodology, O.Y., S.Kh., and V.Kh.; software, T.Z., and L.P.; validation, O.Y., S.Kh., and T.Z.; formal analysis, O.Y., and V.Kh.; investigation, O.Y., S.Kh., V.Kh., and T.Z.; data curation, L.P., and V.Kh.; writing-original draft preparation, O.Y., and T.Z.; writing-review and editing, S.Kh. and L.P.; visualization, O.Y., and V.Kh.; project administration, O.Y. All authors have read and agreed to the published version of the manuscript.

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