

MODERNIZATION OF RAW MATERIAL FEEDING MECHANISM INTO IMPACT BRIQUETTE PRESS

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Abstract. Biomass briquetting presses are classified as extruders, hydraulic piston presses, impact-mechanical presses, and other types. For briquetting biomass with viscoelastic properties (e.g. stalk-based materials), impact presses are the most appropriate. A key requirement of the process is the pre-compaction of the raw material before it enters the pressing chamber. Screw mechanisms feed the biomass into the chamber synchronously with the action of the impact ram. Existing designs exhibit a drawback, namely a low volumetric filling coefficient of 0.4-0.5 between the flights of the compacting screws. This reduces both productivity and briquette strength. According to calculations, the rotational speed of the screws should be within 300-350 rpm. The modernized raw material feeding mechanism consists of two screw units: a horizontal unit and a vertical compacting unit. The shafts of the compacting screws are equipped with pressed-in pins fitted with needle bearings that roll within the screw grooves, representing one of the elements of the modernization. Another improvement involves shaping the first screw flight as a cone. When the ram leaves the pressing chamber, the screw rapidly drops onto the needle bearings, releasing the energy stored in the compressed spring. This design enables a 3-4-fold increase in raw material compaction. For automatic control of chamber filling, the inclination angle of the forming conical section must exceed the friction angle of the biomass against the screw surface and should range from 24° to 68°. Under these conditions, the volumetric filling coefficient reaches 0.8. The modernization of the feeding mechanism improves the dynamic performance of the briquetting press, increases the density of biomass prior to pressing, enhances briquette strength, and ensures higher process reliability. As a result, the press productivity increases by 12-17%, while the wear resistance of the working components improves by 1.2-1.3 times.

Keywords: biomass, briquette press, screw feeder, compacting mechanism, modernization.

Introduction

The high efficiency of biofuel briquettes is explained by their low moisture content (10-15%) and density, which is 7-10 times higher than that of the raw material. This increases the calorific value up to 18-20 MJ·kg⁻¹ and significantly reduces transportation and storage costs by 1.4-1.9 times [1-3].

For efficient thermal conversion of solid biofuels, it is advisable that the briquettes have uniform size and shape. This increases the contact surface area with atmospheric oxygen in combustion systems and improves the combustion efficiency up to 60-75%. The uniformity of the structure and geometric parameters also enhances moisture resistance during storage and improves logistics performance [2-4]. One of the advantages of biofuel briquettes is the long-term stability of their quality due to the relatively high density (900-1100 kg·m⁻³) and the natural protective layer formed during production. Additionally, ash obtained after combustion of the briquettes can be used as a fertilizer [3; 5; 6].

Biomass briquetting presses are classified in several technological types, including extruders, hydraulic piston, impact-mechanical, hammer-type, rotary, and others. Impact-mechanical presses demonstrate particularly high efficiency in briquetting stalk biomass with viscoelastic properties (for example, residues of cereal and groat crops, maize, sunflower, and hardwood waste) [1; 5; 7; 8]. An important condition for efficient briquetting of viscoelastic biomass is the preliminary compaction of the shredded raw material before feeding it into the pressing chamber. It has been established [1; 5; 7; 9] that the most common feeding devices are beater-type and screw mechanisms. Screw feeders of continuous operation with elastic compensation are considered more promising in terms of efficiency [8; 10; 11]. They provide preliminary compaction of the biomass and ensure synchronized forced feeding into the pressing chamber in accordance with the motion of the impact ram. The technological process is carried out automatically. At the same time, existing screw feeder-compactor designs have several disadvantages. These include a low volumetric filling coefficient (0.4-0.5) in the space between the screw flights, imbalance between the feeding mechanism and the pressing ram, and insufficient preliminary compaction of the raw material before pressing. This reduces the overall quality of the

briquettes. The use of additional devices leads to increased complexity and cost of the design, as well as reduced operational reliability of the feeding mechanism [11; 12].

To improve the efficiency of an impact-mechanical briquetting press, it is necessary to modernize the feeding mechanism for plant stalk materials with viscoelastic properties. It should also be taken into account that the moment of instantaneous filling of the pressing chamber depends on the design and operating parameters of the feeder, the stiffness of the compaction springs, and the physico-mechanical properties of the processed materials [8; 11; 13].

Materials and methods

To identify the technical analogue of the raw material feeding mechanism for an impact-mechanical briquetting press, a patent search of known designs was carried out. Among the identified developments, a press for briquetting straw into feed products (patent DE No. 1948418, B30B 11/20) was selected as the technical analogue. This press is equipped with a screw compactor, in which the working body transmits force to the material through a spring. This design ensures continuity of intake and compaction of the plant biomass.

The compactor includes a horizontal and a vertical sections. The horizontal section consists of two synchronized screws that provide mixing of the biomass components, their uniform distribution, and forced feeding into the vertical screws. The vertical section of the compactor consists of two electric drives and screws connected to the drive shafts by means of cylindrical springs.

Such a design of the compactor ensures continuous intake and compaction of the biomass, as well as periodic (impulse) feeding of the compacted material into the pressing chamber followed by its additional compaction as a result of a dynamic impact caused by the energy accumulated in the damper spring during its compression at the moment when the ram exits the pressing chamber. In addition, the damped oscillations of the spring-damper system, caused by the force of the dynamic impact, contribute to further compaction of the formed portion and reduce the friction force between the compacted biomass and the screw flights.

The types of biomass used are summarized in Table 1.

Table 1

Biomass used for experimental studies

Biomass	Weighted average particle, cm	Moisture content, %	Density, kg·m⁻³
Crushed wheat straw	10	17.5	58
Barley straw	14	19.0	41
Grass hay	18	21.0	43
Buckwheat straw	11	18	35

In the present study, the following general methods were employed [7; 8; 11; 14]:

- structural analysis and synthesis of the feeding and compaction process of stalk biomass during filling the pressing chamber of the briquetting press;
- deductive analysis of the movement and transformation of the properties of the viscoelastic biomass on the surfaces of the screw working bodies;
- abstraction of the non-uniform fractional composition and moisture content of the stalk biomass;
- mathematical modeling of the rotational and reciprocating motion of the screws for preliminary compaction and synchronized feeding of the biomass into the pressing chamber.

Results and discussion

To accomplish the stated objective, technical modernization of the screw feeder-compactor of an impact briquetting press was carried out (Fig. 1). The modernized device consists of feeding and compacting mechanisms. The feeding mechanism includes two screw elements 1 and 2, which are equipped with blades 3 at the ends and are synchronized by means of cylindrical gears 4 (section A–A). The screws 1 and 2 are supported by bearings mounted in the housing 5, which is provided with a loading hopper 6. The feeding and compacting mechanisms are connected by means of a flange 7.

The compacting mechanism includes two vertical screws 10 and 11, the shafts of which are connected to hollow drive shafts 12 by means of supports 8 and springs 9. The shafts of the screws 10 and 11 are capable of axial movement within the hollow shafts. Pins 13 are press-fitted into the shafts of screws 10 and 11, on which needle bearings 14 are mounted. These bearings roll in helical grooves 15 on the surface of the shafts 12. The housing tubes 16 are provided with loading windows 17 (section A-A) and outlet openings leading to the chamber 18 with rams 19.

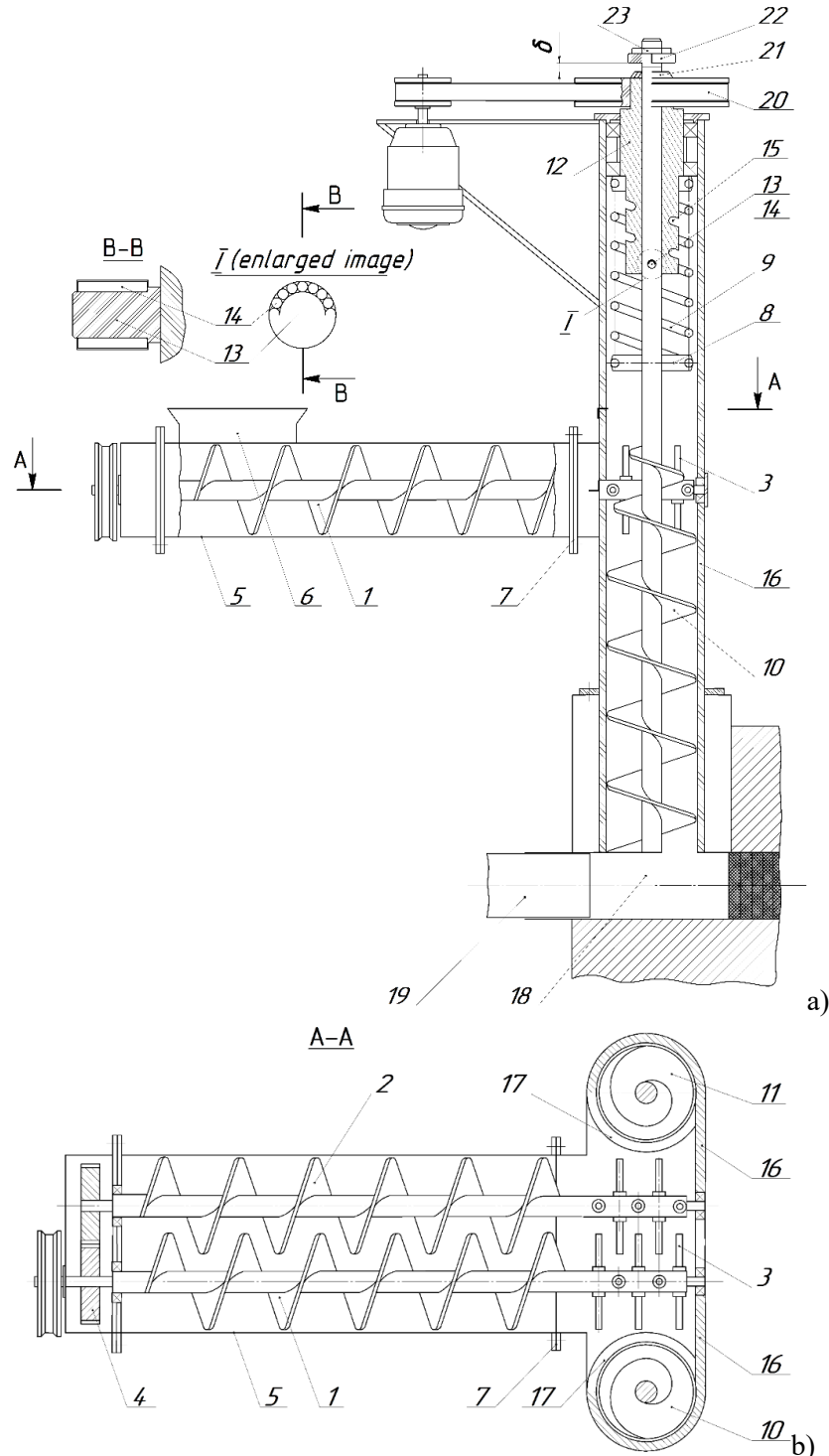


Fig. 1. Design scheme of the modernized screw feeding mechanism for an impact briquetting press: general view (a); 1 and 2 – horizontal screws; 3 – blade; 5 – housing; 6 – hopper; 7 – flange; 8 – support; 9 – spring; 10 and 11 – vertical screws; 12 – drive shaft; 13 – pin; 14 – needle bearing; 15 – groove; 16 – housing tube; 18 – pressing chamber; 19 – ram; 20 – pulley; 21 – disc spring; 22 – nut; 23 – locknut; section A-A (b); 4 – gear; 17 – loading window

Modernization of the design consists in that the vertical screws 10 and 11 are cylindrical, with a first conical flight at the top, and are suspended from the drive shafts by means of springs 9. The pitch of the screw flight is constant along all turns.

The screw feeder-compactor is also modernized by incorporating needle bearings 14, mounted on pins 13 press-fitted into the shafts of the compacting screws, moving within the helical grooves 15 of the drive shafts 12.

In addition, the feeder is modernized so that the amplitude of damped oscillations of the compacting screws 10 and 11 is determined by the clearance between the nut 22 and the disc spring 21, mounted on the hubs of the drive pulleys 20. Disc springs 21 are installed on the hubs of the drive pulleys 20 and absorb the impact load from nuts 22, which are locked by locknuts 23 to form a constant clearance δ that determines the amplitude of damped oscillations of the screws 10 and 11.

To increase the filling density of the screws 10 and 11 and to ensure automatic control of their filling, it is necessary that the angle of inclination of the generatrix of the conical part exceeds the angle of friction of the biomass on the screw surface. When compacting straw with a moisture content of about 18%, the friction angle on steel is approximately 24° . According to the studies [8; 11], the inclination angle of the generatrix of the conical flights should be in the range from 24° to 68° .

During operation, the biomass is fed by the screw 1 through the loading window 17 onto the compacting screw 10. The conical part forces the material into the screw space of screw 10. As the biomass accumulates in the outlet zone, the screw 10 moves upward along grooves 15, and its conical part exits the area of the window 17, which increases the discharge capacity of the screw 10 and reduces its filling density. When the ram 19 releases the pressing chamber 18, the screw 10 moves sharply downward, releasing the energy of the compressed spring 9 and momentarily increasing its rotational speed. When the ram 19 enters the pressing chamber 18, the operation cycle of the compacting screw 10 is repeated. A similar process occurs in the compacting screw 11.

The drive of screws 1 and 2 is controlled automatically. To prevent clogging of biomass in the screws 10 and 11, reversal of their electric drives is implemented.

Such a design of the feeding mechanism enables for preliminary compaction and synchronous feeding of the stalk biomass of variable structural and particle size composition in accordance with the operation of the ram. The length of stalk particles may reach 80–100 mm. The material density prior to pressing by the ram increases by 3–4 times.

Based on the obtained results, a mathematical model of the system “feeding mechanism – briquetting press” was developed:

$$HSL n_r \omega = \frac{\pi^2}{8} (b^2 - d_b^2) (b - 2\delta - d_b) t g \left(\frac{\pi}{4} - \frac{\varphi}{2} \right) \frac{\omega^2}{\omega_0} n_s \xi f C, \quad (1)$$

where H, S, L – height, width, and length of the pressing chamber of the impact briquetting press, respectively;

n_r – velocity of the pressing ram;

ω – density of the material at the outlet of the feed mechanism chamber;

b – distance between the axes of adjacent pressing chambers;

d_b – diameter of the screw shaft;

δ – radial clearance between the edge of the screw and the inner surface of the housing;

φ – friction angle of the material on the screw surface;

ω_0 – initial density of the material entering the feeder;

n_s – rotational frequency of the feeder screw;

ξ – filling coefficient of the screw in the loading zone;

f – coefficient of sliding of the biomass along the inner surface of the feeder housing;

C – coefficient accounting for changes in the feeder productivity.

Analysis of the system model (1) indicates that the parameters are determined by the design of the briquetting press. The parameter values characterize the physico-mechanical properties of the biomass and are determined experimentally or from reference data.

Based on the analysis of the mathematical model (1), it was established that the least influential factors on the specific performance indicators of the system are the geometric dimensions of the pressing chambers and the feeder, as well as the operating frequencies of the working screws and rams.

The most significant constraint on the geometric dimensions of the pressing chamber, and consequently on the size of the fuel briquettes, is imposed by the technological requirements for the specific type of biomass.

To mitigate the negative impact of briquette size on the performance of the impact briquetting press when reducing the dimensions of the pressing chambers, the duration of the material feed pulse (residence time) into the chambers should be shortened. This allows increasing the operating frequency of the press, thereby significantly expanding its technological capabilities.

Stalk biomass has a low bulk density and, consequently, occupies a large volume. The bulk density of shredded straw with particle lengths 30-60 mm and a moisture content 10-14% reaches 55-70 kg·m⁻³. Therefore, the capacity of the feeding mechanism should be equal to or slightly lower than that of the press.

After mathematical transformations [14] with intermediate expressions, the formula for determining the rotational frequency of the compacting screws 10 and 11 (Fig. 1) was obtained:

$$n_s = \frac{8HSLn_r\omega^2}{\pi^2(b^2 - d_b^2)(b - 2\delta - d_b)tg\left(\frac{\pi}{4} - \frac{\varphi}{2}\right)\xi fc\omega_\alpha^2}. \quad (2)$$

Analysis of expression (2) shows that the density ω of the biomass at the outlet of the feeding mechanism exhibits a stepwise dependence on the rotational frequency of the compacting screws 10 and 11 (Fig. 1). That is, the degree of additional compaction, as a function of the spring compression, depends on the amount of material delivered by the screws into the additional compaction zone.

A graphical relationship (Fig. 2) was obtained showing the operating frequency of the compacting screws as a function of the coefficients f, ξ, c when operating with a press having the following design and operating parameters: pressing chamber height $H = 80$ mm; width $S = 160$ mm; length $L = 240$ mm; ram stroke frequency $n_r = 200$ min⁻¹. The design parameters of the biomass feeding mechanism for the press are as follows: radial clearance between the screw surface and the housing of the cylindrical part of the feeder $\delta = 10$ mm; clearance between the screw surface and the additional compaction chamber $\alpha = 30$ mm; diameter of the screw shaft $d_b = 30$ mm; diameter of the screw flight in the cylindrical part $D = 200$ mm; diameter of the screw in the additional compaction chamber $D_1 = 154$ mm; inclination angle of the generatrix relative to the screw axis $\beta = 20^\circ$.

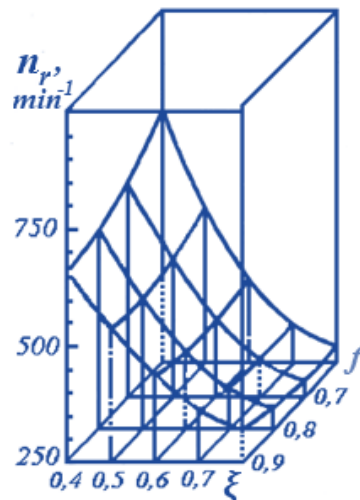


Fig. 2. Dependence of the rotational frequency of the compacting screws on the filling coefficient of the screw working volumes ξ and the coefficient of biomass sliding f along the housing of the feeding mechanism

Calculations were carried out at the angle of friction of wheat straw on the screw surface $\varphi = 38^\circ$ and an initial density $\omega_0 = 50$ to 70 kg·m⁻³. The filling coefficient of the working volumes of the

compacting screw ranges from $\xi = 0.6$ to 0.8 . Experimentally determined values of the coefficient of biomass sliding along the housing are within $f = 0.6$ to 0.9 .

The results of experiments with crushed wheat straw turned out to be basic for other types of stem biomass (barley and buckwheat straw, grass hay). The values of the coefficients ξ and f on these types of biomasses did not exceed 5% of wheat straw [11].

Analysis of the graphs (Fig. 2) shows that as the filling and sliding coefficients decrease, the rotational frequency of the compacting screws increases. In other words, to maintain the specified press capacity when these coefficients decrease, it is necessary to increase the rotational frequency of the compacting screws, which is undesirable due to the resulting higher energy consumption of the process. For example, when the filling coefficient decreases from 0.8 to 0.4 at a sliding coefficient of $f = 0.9$ the rotational frequency of the compacting screws must be increased from 330 to 650 min^{-1} to maintain the specified capacity. Similarly, when the sliding coefficient decreases from 0.9 to 0.6 at $\xi = 0.8$ the rotational frequency of the working screws must be increased from 330 to 520 min^{-1} . The maximum rotational frequency of the working screws occurs at $\xi = 0.4$ and $f = 0.6$. The optimal rotational frequency of the working screws is achieved at a filling coefficient of $\xi = 0.8$ and a biomass sliding coefficient of $f = 0.9$.

Conclusions

1. Impact-mechanical briquetting presses are advantageous for compacting biomass with viscoelastic properties, provided that the material is pre-compacted before being fed into the pressing chamber. The most effective solution is a two-stage screw feeder-compactor with spring compensation. This design allows pre-compaction and intermittent feeding of the biomass with variable structural and particle size compositions. Uniform distribution of the compacted biomass flow prior briquetting improves the dynamic operation of the press and increases its wear resistance by 1.2-1.3 times. The implemented technical and technological modernization of the feeding mechanism increases the press productivity by 12-17%, enhances the process reliability, improves briquette quality, thereby improving the overall efficiency of the modified press.
2. Analysis of the feeding mechanism operation indicates that, as the rotational frequency of the compacting screws decreases from 300 to 100 min^{-1} , the feeding mechanism productivity decreases, while the filling coefficient remains unchanged. Therefore, reducing the rotational frequency of the screws below 300 min^{-1} is not advisable. On the other hand, increasing the rotational frequency from 300 to 400 min^{-1} results in approximately 20% increase in the feeding productivity, but the energy intensity of the process increases by 12%. At frequencies above 500 min^{-1} , no further increase in productivity is observed. Therefore, for practical applications, it is recommended to set the rotational frequency of the compacting screws within the range of $300\text{-}350 \text{ min}^{-1}$.
3. The modernized feeding mechanism allows pre-compaction of the material by a factor of 3-4 times before pressing. For automatic control of filling, the inclination angle of the forming conical section should exceed the friction angle of biomass on the screw surface and lie within the range $68^\circ > L > 24^\circ$. Under these conditions, the volumetric filling coefficient reaches 0.8 .

Author contributions

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

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