INFLUENCE OF PRESSING MODES ON QUALITY INDICATORS OF BRIQUETTES FROM STRAW MATERIALS AND GRAIN WASTE

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Abstract. In experimental studies, the influence of briquetting parameters (pressure, moisture content, and material residence time in the die) on the density of briquettes made from straw, husk, and their mixtures with grain waste was assessed. The results showed that briquette density increases with higher pressure. A mixture of straw and grain waste achieves the highest density – over 900 kg·m^{-3} – at a pressure of 65 MPa, while husk briquettes reach a density of 830 kg·m^{-3} at 90 MPa and straw stalk briquettes achieve up to 800 kg·m^{-3} at pressures exceeding 100 MPa. As the moisture content of the raw material increases, the briquette density also rises, with maximum values achieved at approximately W ≈ 17%. Further increase in the moisture content leads to a decline in the density, but this reduction is minor for mixtures with grain waste due to improved particle adhesion. However, briquettes with a moisture content exceeding 17% are poorly preserved and lose their fodder and fuel value due to microbial damage. The residence time of the material in the die is also crucial for briquette density: with larger loading volumes or shorter die channel lengths, the density decreases. When designing briquetting presses, the interrelationship between productivity and the die channel length must be considered. Laboratory experiments conducted using an impact-mechanical briquetting machine produced briquettes with densities of 0.8-1.0 t·m^{-3} at a frequency of 200 impact motions per minute. The machine's productivity was 2 t·h^{-1} for straw, 2.2 t·h^{-1} for husk, and 2.4 t·h^{-1} for husk and grain waste mixture. Considering the significant accumulation of straw and husk at post-harvest processing points during the harvest season, using an impact press with a productivity of 4 t·h^{-1} would allow these residues to be processed into fodder and fuel briquettes within 200 days. This approach is economically and environmentally beneficial for agricultural enterprises.

Keywords: briquettes, straw materials, grain waste, briquetting parameters.

Introduction

Fuel briquettes produced from secondary biomass derived from agricultural production – such as cereal straw, corn waste, and sunflower residues – hold a significant fuel and energy potential in Ukraine. The prospective annual utilization of such biofuel is estimated at approximately 8.3 million tons of oil equivalent [1]. Additionally, briquetting is a viable solution for rationalizing plant waste [1-4].

Biomass briquettes are an enhanced form of fuel with standardized quality. They serve as an alternative to traditional fossil fuel sources for generating environmentally "clean heat" and, with a calorific value of 16-19 MJ·kg^{-1}, are comparable to lignite coal. For efficient thermal conversion, solid biofuel must be in the form of uniformly sized and shaped products, which enhances contact with atmospheric oxygen in heating installations, improves moisture resistance, and optimizes logistical parameters [2; 3]. Biomass briquettes are categorized into three primary types: RUF, Pini&Kay, and NESTRO (NIELSEN), each named after the manufacturers of the respective briquetting equipment. The design and operational principles classify briquetting presses into stamp (punch), impact, screw, hydraulic-piston, rotary, and vibro-impact presses. NESTRO-type briquettes are produced using stamp presses that operate on an impact-mechanical principle. These briquettes offer advantages such as relatively low production costs, high density (0.9-1.2 t·m^{-3}), and efficiency in storage and transportation. Moreover, impact presses are particularly suited for briquetting materials with viscoelastic properties, such as hay-straw mixtures and grain processing residues for animal feed [2; 5].

The physical essence of the biomass briquetting process lies in the intense compression of material particles, leading to the emergence of molecular cohesive forces. The process unfolds in three stages: in the first stage, the raw material undergoes volume reduction through pre-compaction and air expulsion within the pressing channel. The second stage is characterized by the development of viscoelastic deformations and a rapid increase in the pressing pressure. A portion of the input energy is utilized to deform the biomass and overcome internal friction, both within the material itself and against the press

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channel walls, while another portion is stored within the briquette. In the third stage, the pressure continues to rise with minimal further increase in density. The stored energy in the briquettes represents elastic potential energy, which may lead to structural failure if not adequately managed [5].

Theoretical studies on the briquetting process highlight its complexity and multifactorial nature. The challenge of obtaining robust briquettes from straw and other plant materials has been addressed in various publications [6-10], which analyse the impact of raw material physicomechanical properties on the process dynamics and final product characteristics. However, not all of these studies fully elucidate the phenomenon of compressing straw mass into solid, durable briquettes. Straw materials and grain residues exhibit significant variability in their technological and physicomechanical properties, including the particle size, moisture content, presence of natural impurities, and viscoelastic characteristics [2; 6; 9; 10]. Therefore, refining the analytical and empirical principles of straw-based briquetting is essential for enhancing both the efficiency of production and the utilization of this biofuel.

This study aims to experimentally investigate the impact of briquetting parameters – pressure, moisture content, and material residence time in the die – on the density of briquettes produced from straw, husk, and their mixtures with grain waste.

Materials and methods

Laboratory experiments on impact-mechanical briquetting were conducted using three types of secondary biomass: wheat straw, chaff, and mixtures of straw with crushed grain residues. The experiments were performed using a PBU-060-800 stamp press equipped with a circular die with an internal diameter of 60 mm (Fig. 1). The moisture content of the straw ranged from 12% to 20%, in chaff from 12.8% to 16%, and in the mixtures from 14% to 16%. The particle size distribution of the straw stem fraction varied from 20 mm to 80 mm. All experiments were performed with three replications. The pressing force was determined using an IP-1500 electronic force gauge with an accuracy of ± 1%. The geometric parameters of the briquettes were measured using a calliper. The moisture content of straw materials and grain waste was measured using an ULTRA-X (Germany) moisture meter with a measurement accuracy of ± 1.5%. The briquette density was measured as follows. First, the volume of each briquette was determined, and then the briquettes were weighed on RN-10Ц13 (No. 151234) scales with a measurement accuracy of 0.5 g.

Fig. 1. **Impact-mechanical briquetting press PBU-060-800 for laboratory experiments:** 1 – raw material hopper-feeder; 2 – electromechanical drive of the feeder; 3 – electromechanical drive of the pressing chamber, 4 – pressing chamber; 5 – briquette forming matrix; 6 – control panel; 7 – briquette cooling line (not shown)

The pressing mechanism of the briquetting press consists of the following components: a flywheel with a crank-slider mechanism, a slider with a stamp (punch), a pressing channel, and a matrix channel. The flywheel and crank-slider mechanisms convert the rotary motion of the electric motor shaft into the reciprocating movement of the stamp piston. The energy release of the flywheel occurs over a short 50 mm stroke of the stamp, allowing the development of substantial compression force (pressure) during briquetting [2; 3].

The operation of the briquetting press follows these steps. Biomass is fed into the hopper (1) and transported into the pressing chamber (4) by a screw feeder. Upon impact from the stamp piston, the material is compressed and moves through the matrix channel (5) by the thickness of the briquette. During the return stroke of the stamp, the next portion of biomass is loaded into the pressing chamber. With each subsequent impact, the compressed biomass fuses with the previous portion and is pushed through the matrix channel (5) in the form of a continuous briquette. Upon exiting the matrix, the briquette is cooled in a designated tray of a specific length [2; 3; 10].

Results and discussion

The general relationship between increasing density and higher briquetting pressure [10] is most evident in the briquetting of mixtures containing grain residues (Fig. 2a). This is attributed to the fact that such a technological material exhibits minimal elastic aftereffect compared to straw or chaff. As shown in Fig. 2a, the highest density briquettes, exceeding 900 kg·m^{-3}, were obtained from the mixture of straw and grain residues at a pressing pressure of 65 MPa. Lower-density briquettes, approximately 830 kg·m^{-3}, were formed from chaff at a higher pressure of 90 MPa. The lowest-density briquettes, around 800 kg·m^{-3}, were produced from the stem fraction of straw. Experimental results indicate that straw should be briquetted using an impact method at pressures exceeding 100 MPa.

As the moisture content of straw material increases, the briquette density also rises, reaching its peak at a moisture level of W = 17% (Fig. 2b). Further moisture increases lead to a decline in the density. However, in briquettes containing grain residues, this effect is less pronounced due to the enhanced adhesive properties of the flour-like fraction in the mixture. Industrial experience shows that briquettes with a moisture content exceeding 17% degrade during storage, becoming prone to microbial contamination, partial disintegration, and a subsequent loss of feed and fuel value.

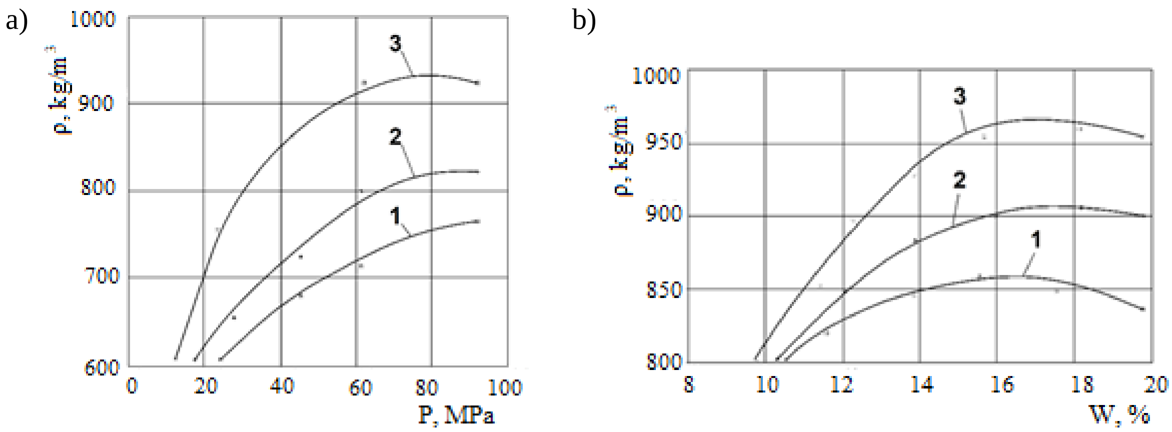

Fig. 2. **Graphical dependencies of briquette density on (a) pressing pressure and (b) raw material moisture content at a pressure of P = 60 MPa:** 1 – straw; 2 – chaff; 3 – mixture of straw and grain residues

One of the key parameters in the briquetting process is the residence time of the material in the matrix under compression (Fig. 3), which allows for relaxation of internal stresses. This factor depends on the amount of the raw material fed into the pressing chamber and the length of the matrix channel. Briquette density is primarily determined by these parameters, which must be considered when designing the press configurations. As the press productivity increases due to a higher feed rate into the pressing chamber, the briquette density (Fig. 3) decreases due to the shorter residence time of the straw-based material in the matrix. A decrease in the matrix channel length also leads to a reduction in the briquette density.

When determining the coefficients of external friction f, it was found that the lowest values correspond to sets 1 and 2 (Fig. 4). The coefficient values were higher for chaff (3) and for the mixture of chaff and grain residues (4). The experimental results indicated that for straw-based materials, within the accepted pressure range of up to 60 MPa, the coefficient of external friction f decreases almost linearly as the applied load (pressure) increases. As a result of the briquetting process using straw, chaff, and mixtures with grain residues on the PBU-060-800 briquetting unit, briquettes were formed with a density of 0.8-1.1 t·m^{-3} at a stamping frequency of 200 strokes per minute. The briquetting productivity was 0.3-0.35 t·h^{-1} for straw, 0.32 t·h^{-1} for chaff, and 0.4 t·h^{-1} for the mixture of chaff and 30% grain residues.

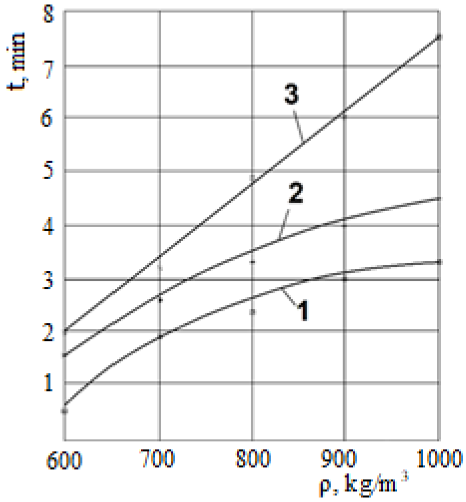

Fig. 3. **Relationship between material retention time in a compressed state (t) and the specified briquette density (ρ):** 1 – straw *W* = 14.6%; 2 – chaff W = 12.8%; 3 – mixture of straw and grain waste W = 14%

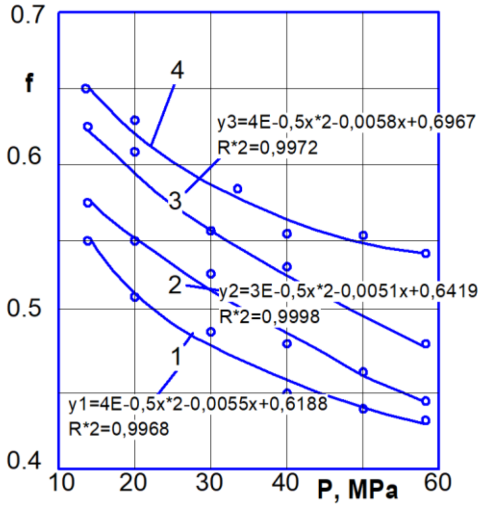

Fig. 4. **Dependence of the friction coefficient (*f*) on pressure (*P*):** 1(y_1) – straw (30-80 mm); 2(y_2) – straw (20-30 mm); 3(y_3) – chaff; 4 – mixture of chaff and 30% grain waste

A design matrix was developed according to the Box–Behnken plan for single-factor experiments $\rho = f(P)$, $\rho = f(W)$, $t = f(\rho)$, *and* $f = f(P)$. Statistical analysis, mathematical processing, and calculation of the regression coefficients were performed using the STATISTICA software. From the experimental data processed in MS Excel using regression analysis, second-order regression equations were derived (an example is shown in Fig. 4). The adequacy of the models of the investigated process was verified using Fisher's criterion, and the statistical significance of the regression coefficients was determined using Student's t-test. Threefold repetition of the experiments with an allowable error of 1.0 fraction ensured a reliability of 0.9 [11]. The relative error in briquette production experiments arose from uneven moisture content, particle size distribution, and other properties of the input material. The error did not exceed 4.3%. Additionally, a randomization method was employed, which allowed the influence of external random factors to be distributed fairly evenly throughout all the experiments [11].

In the discussion of the obtained results on the briquetting of straw materials and mixtures with grain waste, a proposal is put forward regarding the feasibility of technical and technological modernization of the process. One of the modernization approaches involves developing a design in which the working end surface of the stamp piston (Fig. 5a) has a zigzag shape divided into three equal parts (Fig. 5b) along the diameter D_p of the piston. The upper and lower parts have vertical projections, while the middle part is inclined at an angle of 45°, so that the plane of the lower part is shifted toward the reverse stroke of the piston by a distance of $D_p/3$ sin 45°. At the moment of impact by the stamp piston, the lower part compresses the biomass with a certain time offset but maintains the nominal pressing performance [12].

The briquetting press includes a loading hopper 1 (Fig. 5a) with a screw feeder 2, a housing 3, and a crank-connecting rod mechanism 4, which drives the stamp piston 5 in an impact motion. Moving towards the die 6, the stamp, having gained significant kinematic force from the mechanism 4 with a flywheel, intensively compacts the straw in the pressing chamber and, continuing its movement within the die 6, compresses the dispersed raw material into monolithic briquettes 7. The length of the die 6 is of significant importance, as during the briquette formation inside it, stress relaxation in the compressed straw must occur to ensure the strength of the briquettes. Due to the design of the working end of the stamp piston 5 (Fig. 5b) in the form of a zigzag-shaped surface with three equal-height sections (*A*, *B*, *C*), the process of preliminary straw densification and subsequent impact-driven pressing into briquettes 7 achieves higher technological efficiency. This is explained by the fact that due to inertia straw does not evenly fill the pressing chamber upon entry. In the lower section *C*, the density remains lower, as depicted in Fig. 5 with a lighter shading. Consequently, when pressing with a flat-surfaced stamp piston 5, cracks form at the junctions of the briquette components, significantly reducing their strength and, accordingly, their quality.

In the design of the pressing unit, the upper section *A* (Fig. 5b) of the piston's end surface 5 begins to compact the straw, which partially moves into the middle section *B*. Since the angle $\alpha = 45°$ is smaller than the friction angles of biomass on steel (24°-39°), the resistance forces are negligible. As a result, the density within the chamber equalizes, and the lower section *C* generates pressing forces with indicators comparable to those of the other sections of the piston's end surface 5. Additionally, the surface area of the zigzag-shaped end is larger than that of a flat surface, which enhances the dry diffusion process in the briquettes between the straw batch connections [12].

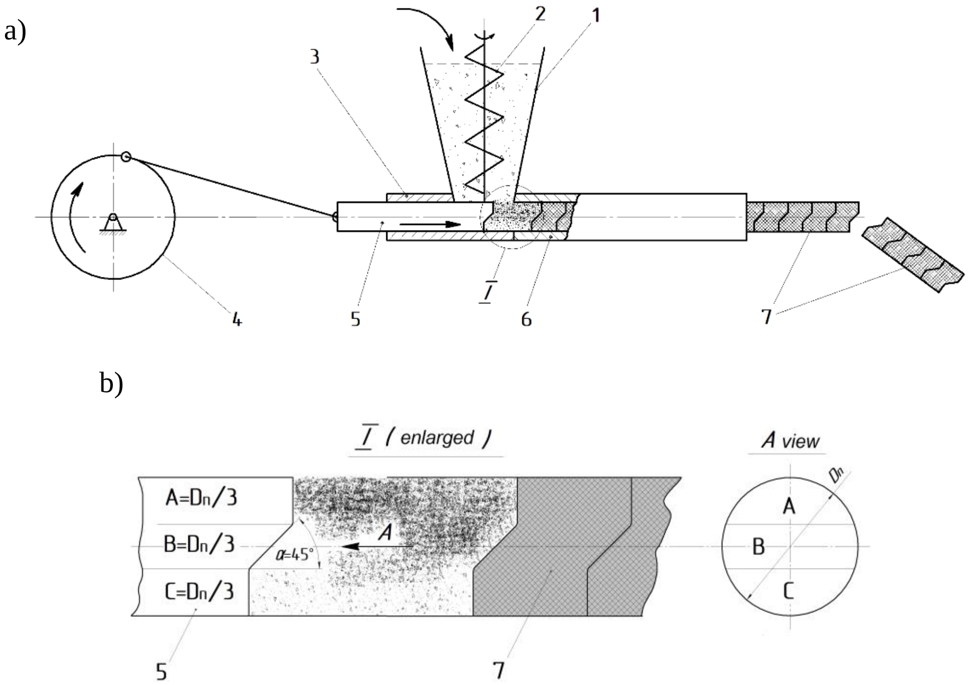

Fig. 5. **Structural and functional diagram of the modernized impact briquetting press; general view (a); end section of the stamp piston 5 with enhancement elements (b):** 1 – loading hopper; 2 – feeder; 3 – housing; 4 – flywheel; 5 – stamping piston; 6 – die; 7 – briquettes

Thus, the proposed zigzag-shaped end surface of the stamp piston facilitates the production of higher-quality briquettes in terms of strength characteristics. This is achieved by finalizing the straw mass compaction within the pressing device at the stamp piston impact. Additionally, the connecting area between the straw batch compounds increases, enhancing the dry diffusion process in the briquettes while they remain in the die.

Conclusions

1. Laboratory research has demonstrated the effectiveness of an impact-mechanical installation for briquetting straw-based materials with complex elastic-viscous properties. At a pressing pressure of 60 MPa, briquettes produced from mixed materials achieved the highest density – exceeding 900 $kg \cdot m^{-3}$ – due to a reduced elastic aftereffect compared to pure straw. For optimal results, briquetting straw with a particle size of approximately 80 mm is recommended at a pressure exceeding 100 MPa.
2. As the pressing pressure increases, the external friction coefficients (f) decrease across all tested materials. This inverse relationship is particularly evident in coarsely chopped straw, which exhibits the lowest friction coefficients. In contrast, the highest friction coefficients are observed in the mixture of chaff and grain waste. These findings suggest that material composition and the particle size significantly influence friction behaviour during the briquetting process.

3. For efficient briquetting of plant-based materials with high relaxation properties, such as straw, it is advisable to maximize raw material compaction within the feeding device and minimize the briquette growth length per punch pass. This leads to a more uniform density and an increase in the product strength by a factor of 1.2-1.5 However, it results in 8-10% reduction in the briquette production efficiency.

Author contributions

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

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