Розроблено процес пресування паливних брикетів з осіннього листя. Показано, що сферична форма брикету – оптимальна, бо навіть щільне упаковування куль забезпечує доступ повітря до кожної окремої кулі. Це особливо важливо в початковій фазі горіння, коли брикети торкаються один одного та набирають певну температуру: якість горіння підвищується. Розроблено технологію пресування брикетів. В результаті дослідження дисперсності часток сухого листя горіха, клену та дуба після подрібнення встановлено, що розподіл за розмірами часток порошків із різного листя не однаковий, а їх насипна щільність пропорційна розміру за найбільшим вмістом.

Запропоновано новий спосіб пресування брикетів у круглій закритій матриці, який відрізняється тим, що процес здійснюють при створенні в кінцевій фазі схеми всебічного рівномірного стиснення з сферичним прикладанням зусилля та з утворенням брикету форми кулі. Спосіб дозволяє радіально та рівномірно стиснути здрібнене листя і тим самим забезпечує однакові умови горіння брикету в радіальному напрямку з будь-якої точки периферії. Отримано математичну модель залежності щільності сухих брикетів від насипної щільності подрібненого листя та ступеня стиснення брикету (величини деформації). Показано, що найбільший вплив на щільність сухих брикетів виявляє насипна щільність подрібненого листя (65 %), із підвищенням якої щільність сухих брикетів збільшується. Вплив ступеня стиснення брикету значно менший (35 %), але має суттєве значення. З його підвищенням щільність сухих брикетів збільшується. В рамках експерименту щільність сухих брикетів складала 0,67 до 1,07 г/см³. Запропоновано конструкцію закритої циліндричної матриці з перемінною за товщиною стінкою, яка дозволяє зменшити її металомісткість і вартість на 20–30 %. Показано, що сферичні брикети із листя доцільно використовувати як альтернативне екологічно чисте паливо

Ключові слова: технологія пресування, сферичний брикет, осіннє листя, щільність брикету, горіння брикетів

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PRESSING TECHNOLOGY AND BURNING QUALITY OF SPHERICAL FUEL BRIQUETTES MADE FROM AUTUMN LEAVES

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1. Introduction

Autumn leaves can burn as the gluten-containing substance. Therefore, one can consider them as an alternative energy source with great potential. The European Union is urging Member States of Energy Cooperation to increase a share of renewable energy sources by 20 % by 2020 through the relevant directive [1]. Ukraine takes it positively in general [2]. But we almost do not use this raw material in Ukraine at present. They take thousands of tons of autumn leaves away from urban parks and squares to landfills where they rot, emit odors, burrow into the ground, or burn in fires, which violate certain environmental regulations. Therefore, one should pay particular attention to the use of autumn leaves as biofuel, as a cheap raw material for the production of fuel briquettes.

It is in principle possible to press briquettes of various shapes. There are cylindrical briquettes, cylindrical briquettes with a central shutter, solid parallelepiped shaped briquettes, and parallelepiped shaped briquettes with a shutter, hexagonal cross-section briquettes with a shutter and hexagonal cross-section briquettes without a shutter widely used. But we do not know what shape of a briquette is the best. The density of briquettes varies from 0.6 g/cm^3 to 1.3 g/cm^3, and their sizes range from 25 mm to 300 mm. All technological parameters of briquettes affect the burning process, in particular uniformity of burning in the initial phase of the process.

The idea of optimization of a shape of a briquette pressed of autumn leaves is expedient to ensure uniformity of burning in the initial phase of the process when a group of briquettes touches each other. Actually, this determines the relevance of the study aimed at the improvement of the technology of pressing and improvement of the quality of burning briquettes of autumn leaves.

2. Literature review and problem statement

As one knows, biomass is a raw material for biofuels [3]. It is of organic origin. Study [4] presents the physical-and-chemical characteristics of briquettes of different raw materials. Work [5] studies the use and composition of bio-carbon briquettes of organic waste. The authors of all works mentioned above do not consider autumn leaves as a biological raw material for fuel.

At the same time, one should consider autumn leaves as biomass as well. They have certain advantages. They renew year after year, they are environmentally friendly, they contain little sulfur, their burning does not lead to the formation of nitrogen oxides, and their use reduces an amount of urban waste and contributes to the overall improvement of the environment. The authors of work [6] made the first attempts to use autumn leaves for the production of alternative fuels (compact fuel tablets and pellets). They demonstrated the expediency of processing (pressing) of autumn leaves into biofuels in the form of briquettes.

Today, there are fuel briquettes of other raw materials of different shapes, up to 300 mm long (Fig. 1) [7]. As one knows [8], biomass becomes denser during pressing, which makes it possible to use briquettes for energy production effectively.

Fig. 1. The shape of briquettes made from vegetable waste

However, the issues regarding the optimization of technological parameters of pressing of briquettes of autumn leaves remain unresolved.

The authors of paper [9] show how to transform fallen leaves into logs. One knows that rain-moist autumn leaves burn poorly and it seems weird to use them as fuel. However, the dried and properly pressed fallen leaves are high-calorie fuels. The production technology of such ecological firewood includes not only drying and compaction of biomass. It is necessary to add wax into ecological firewood, as it binds and plays the role of additional fuel. The ingredients are as follows: 70 % of leaves and 30 % of wax, so Birmingham logs are 70 % carbon-neutral. Independent tests show that such «firewood» gives 27.84 MJ/kg of thermal energy, which is comparable to the heat of burning high-quality coal and it is more than burning of wood.

A pack of ten logs costs 56 conditional monetary units including delivery through the country, which is comparable to competing eco-products of a similar purpose, such as «synthetic firewood» for fireplaces and stoves made of wood chips. But the latter contains 70 % of wax.

Thus, a large proportion of wax (30 to 70 %) makes briquettes expensive.

The authors of work [10] inform that there is a new economic source of energy of autumn leaves, knots, etc. developed and patented. They propose to the city to resolve two problems at once: to clean streets of leaves and waste and to obtain alternative fuel, which would save valuable gas greatly. They obtain briquettes by pressing leaves, wood chips (it is possible to use also tree bark, straw, hay, corn, and sunflower waste, etc.) at a certain temperature and with a special viscous component based on ordinary wood dust. According to the inventor, leaf briquettes are more useful and economical than coal or gas and give up to 6 Kcal of heat per kilogram of fuel. And an approximate cost of the alternative energy source is 0.03 conditional monetary units for one kilogram. It is advisable to install one line for the production of fuel briquettes within a service radius of 5 km. Such a line occupies no more than 200 m^2 together with utility rooms.

As one can see, it is in principle possible to press briquettes of different shapes. But there is no clear answer which shape is the most rational. In addition, a range of changes in the density of pressed briquettes is quite large (0.6–1.3 g/cm^3) and their length reaches 300 mm. All these technological parameters of briquettes affect the burning process, in particular the duration of burning. But the work [10] does not answer the question about optimal technological parameters of briquettes.

The authors develop the idea of optimization of technological parameters of briquettes. A base of the proposed method is the well-known results of experimental studies [11]. The authors burned briquettes of several different shapes and density and equal initial weight at the same time and fixed duration of their burning. They observed the longest burning duration in solid briquettes (without holes) of higher density. However, they fired all briquettes with chips, which created certain gaps between surfaces of briquettes for the passage of air. If the shape of a briquette provides gaps for the passage of air, then there is the intensification of the initial burning phase. That is why there is the creation of all-embracing uniform compression with the spherical application of force and with the formation of a spherical briquette in the final phase of the scheme of the process in the proposed method.

Thus, the spherical shape of a briquette is the best, because even tight packing of balls provides access of air to each individual ball (Fig. 2).

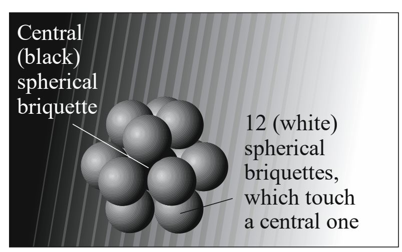


Fig. 2. The model of tight packing of spherical briquettes

This is especially important in the initial phase when briquettes touch each other and gain a certain burning temperature. In addition, the spherical shape of a briquette must ensure its uniform (in the radial direction) and complete burning. However, there were no spherical briquettes of leaves manufactured before this study. They were not objects under study. Therefore, the quality of their burning is unknown. All the above allows us to suggest that it is advisable to carry out a study on the technology of pressing and quality of burning of briquettes of autumn leaves.

3. The aim and objectives of the study

The aim of this study is to optimize technological parameters for pressing briquettes from autumn leaves. Thus, it will improve the efficiency of their burning, especially in the initial phase.

To accomplish the aim, the following tasks have been set:

– improvement of the technology of pressing of briquettes of autumn leaves by using a new technological scheme of formation of a spherical briquette;

– testing of spherical briquettes for burning.

4. Materials and methods to study the process of pressing spherical briquettes from autumn leaves

4. 1. Methodology of improving the technology of pressing briquettes from autumn leaves

The methodology consists of several separate techniques. It implies:

– proposition [12] and theoretical study of a new technological scheme of briquette formation by the description of its technological capabilities;

– experimental study of particles of dry leaves after grinding;

– experimental study of the process of pressing of spherical briquettes;

– testing of spherical briquettes for strength.

We used leaves of nutwood, maple, and oak in the experimental study of the pressing process of spherical fuel briquettes. Studies of the structure of autumn leaves performed on maple leaves (Fig. 3) showed the following. A leaf has a flat leaf plate. The thickness of a leaf plate does not exceed 0.1 mm. The thickness of a cutting lies in the range from 1 to 2 mm. The relative rigidity of a leaf characterized by the ratio of its largest width to the thickness of a leaf plate reaches 2,000. Stiffed capillary thickenings, up to 0.5 mm of thickness, go fan likely from cutting on a leaf plate to supply a leaf with fluid. They give a leaf additional rigidity.

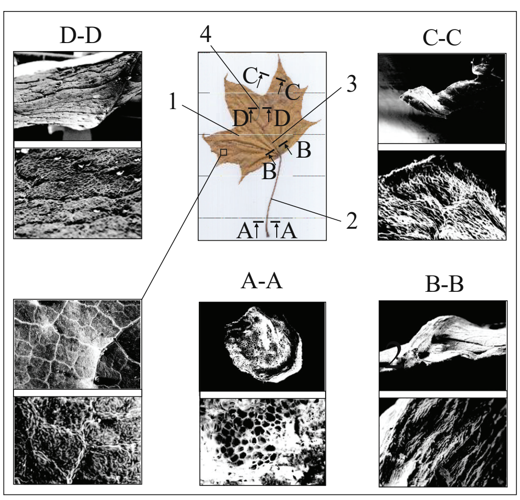


Fig. 3. The structure of autumn maple leaves in the fractograms of its elements: 1 – leaf plate; 2 – cutting; 3, 4 – capillary thickenings of I and II order, respectively (magnification: top ×40; bottom ×200)

As one can see, the structure of an autumn leaf is heterogeneous. In addition, autumn leaves are not uniform by the degree of withering. Moreover, autumn leaves have a large volume. All these reasons substantiate a need to pre-grind leaves. That is why we applied the following technological sequence of obtaining briquettes of fallen leaves in the experimental studies:

– collection of leaves into bags and separation of metal and unwanted objects from them;

– grinding of leaves using a screw shredder (first compaction in the direction of increasing of density);

– pressing of pre-ground leaves into a closed matrix (second compaction in the direction of increasing density).

There is a new technological scheme of briquette formation used in the method of pressing of briquettes of vegetable waste in the proposed closed matrix [12] (Fig. 4).

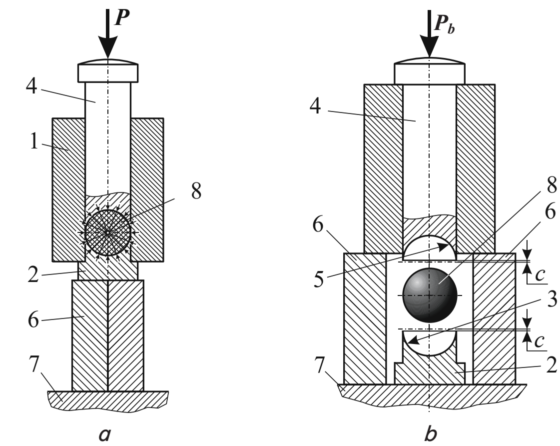


Fig. 4. The scheme of the device for implementation of the method of pressing of briquettes of vegetable waste in a round closed matrix: *a* – final phase of pressing; *b* – phase of ejection of a briquette from the matrix; 1 – matrix; 2 – fixed punch; 3, 5 – hemispherical work surfaces; 4 – movable punch; 6 – stands; 7 – press table; 8 – spherical briquette

The process occurs at the creation of all-embracing uniform compression with the spherical application of force and with the formation of a ball-shaped briquette in the final phase of the scheme. The device for implementation of the method has a round (cylindrical) matrix 1 closed by fixed punch 2 at the bottom with hemispherical work surface 3, and movable punch 4 with hemispherical work surface 5. In addition, the device has two stands 6 with equal height. We install the device on Table 7 of a hydraulic press (not shown in Fig. 8). We load ground vegetable waste (raw material) in the capacity of matrix 1 and insert punch 4. Further, we compress the raw material in matrix 1 with punch 4 on the hydraulic press by P force when moving punch 4 down. Thus, as the working surfaces of punches 2, 4 have a spherical shape, there is a scheme of all-embracing uniform compression with the spherical application of force and with the formation of ball-shaped briquette 8 created in the final phase of the process. We stop the process when it achieves a certain pressing force, which provides the guaranteed formation of spherical briquette 8, but punch 4 does not touch punch 2. Preliminary grinding of sharp edges of the punches by c value facilitates this. Then, we slide stands 6 apart and install matrix 1 on them, and eject punch 2 together with briquette 8 from matrix 1. The uniform compression of briquette 8 guarantees a uniform radial distribution of density over its volume, and therefore, the uniformity of its burning.

The subjects of our study were dried leaves of nutwood, maple, and oak. We pre-ground leaves using a screw shredder (Fig. 5). As one can see below, the leaves became a powder after grinding.

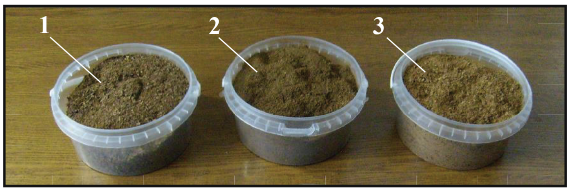


Fig. 5. Dry leaves after grinding: 1 — nutwood; 2 — maple; 3 — oak

We measured the moisture content of leaves powder according to the method described in works [13, 14], taking into account recommendations from paper [15]. We took a sample of 5 g and placed it in a pre-weighed aluminum weighing bottle and kept it in SNOL-120/350 drying oven for five hours at 105 °C. After drying, we placed the weighing bottles in a dry desiccator for cooling. Next, we weighed the weighing bottles with powder on the scales with the accuracy of hundredth of a gram and calculated W moisture content of the powder by the formula:

$$W = \frac{m_1 - m_2}{m_1} \cdot 100\,\%, \quad (1)$$

where m_1 is the weight of a sample before drying; m_2 is the weight of a sample after drying.

Table 1 gives the results of weighing and calculations.

We checked the leaves powder for radiation using the MKS-07 dosimeter-radiometer. The measurements results were as follows:

– the natural radioactivity (natural background) was 16 μR/h;

– the radioactivity of the leaves powder was also 16 μR/h.

We distributed the powder by fractions and studied their dispersion by the method of sieve analysis [16]. We installed a standard set of sieves on a sieving machine and poured 100 g of the powder into a top sieve.

We poured the powder carefully from each of the sieves into separate containers for further analysis after sieving.

The sieve analysis of ground leaves contained the following measurements and calculations for each fraction: a measurement of ΔQ weight using electronic scales with an accuracy up to 0.01 g, a calculation of Δd range of particle sizes in mm, a calculation of density of mass distribution in $\Delta Q/\Delta d$ range of particle sizes in g/mm, a calculation of percentage content, %, a calculation of an averaged d value of size in mm, a calculation of ordinate of the total curve by minus in %, a calculation of ordinate of the total curve by plus in %.

We recorded P pressing force depending on h vertical movement of the punch during the pressing of spherical briquettes (Fig. 6).

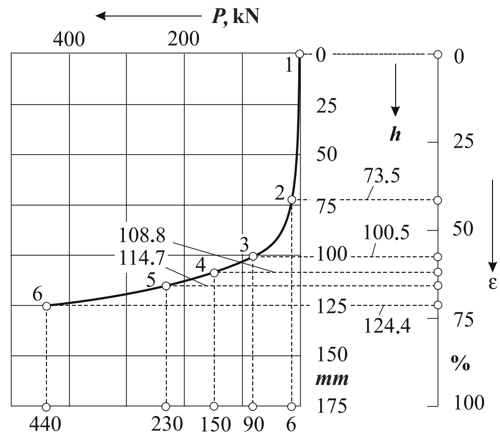


Fig. 6. Experimental curve of the dependence of P pressing force of a spherical briquette of dry ground leaves on h vertical movement of the punch and ε degree of deformation

As one can see, the P_i force of pressing of spherical briquettes of autumn leaves changed according to a certain law when we move h punch down. The force was small at the beginning of pressing. Then, it increased nonlinearly, because of the extraction of air from raw material due to compression and formation of a compact body with a certain density. Therefore, the walls of the matrix experienced different loads across their height.

That is why we suggest that e_i wall thickness (mm) should be proportional to P_i compression force (MN) in the given section (Fig. 7) for each section of matrix 2 across the height.

We determine the e_i thickness of a wall from formula (2) obtained based on provisions of the hydrostatics for a pipe under pressure [17], taking into account k coefficient of a strength factor of a wall:

$$e_i = \frac{k \cdot 2P_i}{\pi \cdot \sigma_b \cdot D}, \quad (2)$$

where σ_b is the limit tensile strength of the material, MPa; D is the inner (working) diameter of the matrix, mm.

The proposed matrix with variable wall thickness for pressing of briquettes has less (by 30–35 %) metal content, and therefore, it costs less.

We used the matrix 3 with variable wall thickness in the experimental punch (Fig. 8). But it had the simplified shape of the outer rotation of a wall profile. The profile had the shape of a truncated cone.

A matrix of such shape is more technological for manufacturing.

We calculated the density of a spherical briquette from the following formula after pressing:

$$\rho = \frac{M}{V} = \frac{M \cdot \pi \cdot d^3}{6}, \quad (3)$$

where M is the weight of a briquette, g; V is the volume of a briquette, cm^3; d is the diameter of a briquette, cm.

Table 1

The results of measurements of the moisture content of leaves powder

Sample No.	Weight of an empty weighing bottle, g	Weight of a weighting bottle with a sample before drying, g	Weight of a weighting bottle with a sample after drying, g	Powder moisture, %
1	25.97	30.97	30.43	1.74
2	25.34	30.34	29.91	1.41
3	20.36	25.36	24.95	1.61
4	22.70	27.70	27.18	1.87
5	22.90	27.90	27.41	1.76
Average value of W powder moisture				1.68

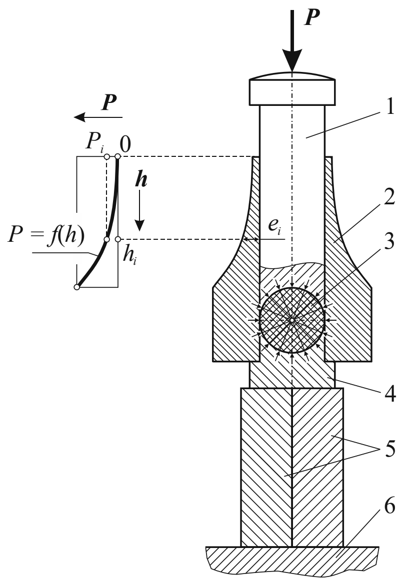


Fig. 7. The scheme of a punch for pressing of spherical briquettes with a round matrix with the wall thickness proportional to P_i current force of pressing of briquette in each section along the height: 1 – movable punch; 2 – matrix; 3 – spherical briquette; 4 – stationary punch; 5 – stands; 6 – press table

Fig. 8. Experimental punch for pressing of spherical briquettes in the disassembled state: 1 – cutting ring; 2 – fixed punch; 3 – matrix; 4 – movable punch with a node of fastening of a ruler; 5 – stands

We applied mathematical methods of experiment planning to build the dependence of ρ_d dry briquette density on factors, which determined a mode of pressing. Based on the preliminary studies, we chose two factors, which influenced ρ_d density of a dry briquette (Table 2). They were the bulk density of ground leaves, $\rho_p(X_1)$, g/cm^3 and a degree of compression (magnitude of deformation) $\varepsilon(X_2)$, % (Fig. 6). The chosen factors satisfied conditions of controllability, operationality, and uniqueness.

We fixed other parameters of the process for pressing spherical briquettes at the following constant levels: diameter of a spherical briquette d_b=50 mm; a characteristic of the matrix was round (cylindrical), d_m=50 mm; the height of filling of the ground leaves in the matrix, mm: a minimum height – 162.5 mm, which corresponded to the degree of compression $\varepsilon(X_2)$=69.0 %, a middle height – 186.5 mm, which corresponded to the degree of compression ε=72.5 %, and maximum height – 210.5 mm, which corresponded to the degree of compression ε=76.0 %.

We calculated the ρ_d density of a dry briquette from the following formula after the experiment:

$$\rho_d = \frac{M_d}{V}, \tag{4}$$

where M_d is the weight of a dry briquette, g; V is the volume of a spherical briquette, cm^3.

$$V = \frac{\pi d_b^3}{6}. \tag{5}$$

Table 1 gives the results of the calculations.

The values of factors in code and natural scales are linked via ratios:

$$x_1 = \frac{X_1 - 0.23}{0.02}; \tag{6}$$

$$x_2 = \frac{X_2 - 72.5}{3.5}. \tag{7}$$

The problem is reduced to the construction of a linear mathematical model in the following form:

$$y = b_0 + bx_1 + bx_2, \tag{8}$$

where b_0, b_1, b_2 are the regression coefficients of the model.

Table 2

The matrix for experiment planning (2^2 plan)

Factor		Bulk density of ground leaves (Table 8), ρ_p, g/cm^3	Degree of compression (magnitude of deformation), ε, %	Density of a dry briquette, ρ_d, g/cm^3
Basic level (X_{io})		0.23	72.5	
Variation range (ΔX_i)		0.02	3.5	
Upper level (X_i=+1)		0.25	76.0	
Lower level (X_i=+1)		0.21	69.0	
Code		x_1	x_2	y
Experiment number	1	+	+	1.07
	2	–	+	0.87
	3	+	–	0.99
	4	–	–	0.67
Experiments at the center of the plan	1	0	0	0.91
	2	0	0	0.89
	3	0	0	0.90
	4	0	0	0.89

We calculated mathematical models of ρ_d density of dry briquettes according to the method described in work [18]. We calculated the variance of the experiment (S_y=0.01658). We calculated regression coefficients of the model (b_0=0.90; b_1=0.13; b_2=0.07). We checked the statistical significance of the regression coefficients (a confidence interval of the regression coefficients (Δb_i=0.015). We constructed the regression equation (y) and a mathematical model (ρ_d) of the density of dry briquettes and tested the hypothesis of the adequacy of the model by Student's t-test.

Spherical briquettes should have some mechanical strength for their transportation, storage, and use because destroyed briquettes do not have advantages of the intact ones [19, 20]. We created a device based on a table drilling machine (Fig. 9) to test spherical briquettes for strength.

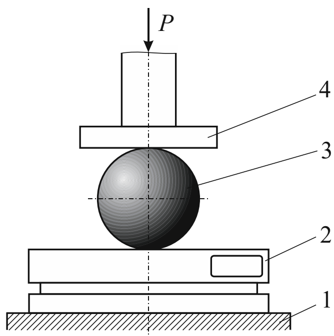


Fig. 9. Diagram of the device for testing spherical briquettes for strength: 1 – table of a machine; 2 – electronic scales; 3 – briquette; 4 – flat tile

We placed ST1231 electronic scales on table 1 of the machine. It was possible to load a briquette 3 up to 1,500 N with an accuracy of 1 N on the scales. We placed the briquette 3 using the feed mechanism of the machine spindle (there is no mechanism on the scheme). We loaded the briquette 3 with P force through the flat plate 4 until the moment of appearance of a vertical crack. We fixed P force, which corresponded to the appearance of a crack. We carried out tests both in the direction of compression of spherical briquettes and in the perpendicular direction.

4. 2. Methodology for testing spherical briquettes for burning

The technique involved the simultaneous burning of three fuels. Each portion weighed 1 kg:

– dry firewood: density – 0.70 g/cm^3;

– RUF fuel briquettes made by pressing of wood chips of oak firewood: density – 1.06 g/cm^3;

– proposed spherical briquettes made of maple leaves: density – 1.07 g/cm^3 (Fig. 10).

Fig. 10. Eleven spherical briquettes of maple leaves prepared for testing for burning

We placed each type of fuel on a separate metal pallet, which made it possible to control the mass of ash after the test (Fig. 11, a). We used the «Spalakh» eco-briquette made of wood wool and impregnated with natural kinds of paraffin for firing.

We measured temperature when fuel was burning (Fig. 11, b). We used a non-contact infrared pyrometer manufactured by Benetech of GM-1150 type to measure temperature. A measurement step was 5–10 minutes. Measurement accuracy was 0.1 °C. We made measurements under MAX mode by scanning of a burning area, that is, the device showed the maximum temperature of all possible measurements. The distance of the device from an object of burning was 1 m. The size of the spot surface to be measured was 50 mm at this distance. We repeated measurements 3 times with the subsequent calculation of an average value.

Fig. 11. Tests of spherical briquettes for burning: a – initial phase; b – intermediate phase (burning process); c – final phase; 1 – firewood; 2 – RUF briquettes; 3 – spherical briquettes

We weighed burning residues left on pallets and calculated a percentage of ash after burning of all fuels (Fig. 11, c). We built a dependence of t burning temperature on T burning time for each fuel and performed a comparative analysis of the burning process according to the test results.

5. Study results

5. 1. Results of improving the technology of pressing briquettes of autumn leaves using a new technological scheme for the formation of a spherical briquette

Tables 3–5 show the results of the analysis for ground leaves of nutwood, maple, and oak. The results made up a basis for the construction of the graphical distribution of powder particles of nutwood leaves (Fig. 12), maple leaves (Fig. 13) and oak leaves (Fig. 14) by sizes.

We studied the shape of powder particles of each fraction by optical microscopy. Table 6 gives the study results.

Table 3

The results of sieve analysis of ground nutwood leaves

# sieve	Fraction, mm	Weight, ΔQ, g	Range of sizes of particles in a fraction Δd, mm	$\Delta Q/\Delta d$, g/mm	Content, %	Average value of a size d, mm	Ordinate of the total curve by minus, %	Ordinate of the total curve by plus, %
1.600	–2.500...+1.600	11.19	0.900	12.43	11.70	2.050	100.00	11.70
1.000	–1.600...+1.000	18.00	0.600	30.00	18.82	1.300	88.30	30.52
0.630	–1.000...+0.630	19.00	0.370	51.35	19.87	0.815	69.48	50.39
0.315	–0.630...+0.315	17.90	0.315	56.82	18.72	0.473	49.61	69.11
0.160	–0.315...+0.160	15.00	0.155	96.77	15.68	0.238	30.89	84.79
0.100	–0.160...+0.100	5.53	0.060	92.17	5.78	0.130	15.21	90.57
0.063	–0.100...+0.063	4.27	0.037	115.40	4.46	0.081	9.43	95.03
0.050	–0.063...+0.050	2.92	0.013	224.61	3.05	0.056	4.97	98.08
0.000	–0.050...+0.000	1.83	0.050	36.60	1.92	0.025	1.92	100.00
Total		95.64	–	–	100.00	–	–	–

Table 4

The results of sieve analysis of ground maple leaves

# sieve	Fraction, mm	Weight, ΔQ, g	Range of sizes of particles in a fraction Δd, mm	$\Delta Q/\Delta d$, g/mm	Content, %	Average value of a size d, mm	Ordinate of the total curve by minus, %	Ordinate of the total curve by plus, %
1.600	–2.500...+1.600	3.04	0.900	3.38	3.20	2.050	100.00	3.2
1.000	–1.600...+1.000	8.89	0.600	14.82	9.35	1.300	96.8	12.55
0.630	–1.000...+0.630	15.41	0.370	48.92	16.20	0.815	87.45	28.75
0.315	–0.630...+0.315	18.79	0.315	59.65	19.76	0.473	71.25	48.51
0.160	–0.315...+0.160	18.00	0.155	116.13	18.93	0.238	51.49	67.44
0.100	–0.160...+0.100	16.00	0.060	266.67	16.82	0.130	32.56	84.26
0.063	–0.100...+0.063	10.00	0.037	270.27	10.51	0.081	15.74	94.77
0.050	–0.063...+0.050	3.48	0.013	267.69	3.66	0.056	5.23	98.43
0.000	–0.050...+0.000	1.49	0.050	29.8	1.57	0.025	1.57	100.00
Total		95.1	–	–	100.00	–	–	–

Table 5

The results of sieve analysis of ground oak leaves

# sieve	Fraction, mm	Weight, ΔQ, g	Range of sizes of particles in a fraction Δd, mm	$\Delta Q/\Delta d$, g/mm	Content, %	Average value of a size d, mm	Ordinate of the total curve by minus, %	Ordinate of the total curve by plus, %
1.600	–2.500...+1.600	5.48	0.900	6.09	5.72	2.050	100.00	5.72
1.000	–1.600...+1.000	11.56	0.600	19.27	12.07	1.300	94.28	17.79
0.630	–1.000...+0.630	20.00	0.370	54.04	20.86	0.815	82.21	38.65
0.315	–0.630...+0.315	22.51	0.315	71.46	23.48	0.473	61.35	62.13
0.160	–0.315...+0.160	17.50	0.155	112.90	18.26	0.238	37.87	80.39
0.100	–0.160...+0.100	6.51	0.060	108.50	6.79	0.130	19.61	87.18
0.063	–0.100...+0.063	5.48	0.037	148.11	5.72	0.081	12.82	92.9
0.050	–0.063...+0.050	4.09	0.013	314.61	4.26	0.056	7.10	97.16
0.000	–0.050...+0.000	2.72	0.050	54.4	2.84	0.025	2.84	100.00
Total		95.85	–	–	100.00	–	–	–

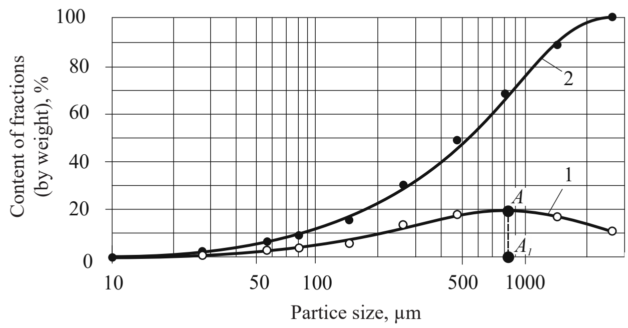


Fig. 12. The distribution of powder particles of nutwood leaves by sizes: 1 — differential curve; 2 — integral curve

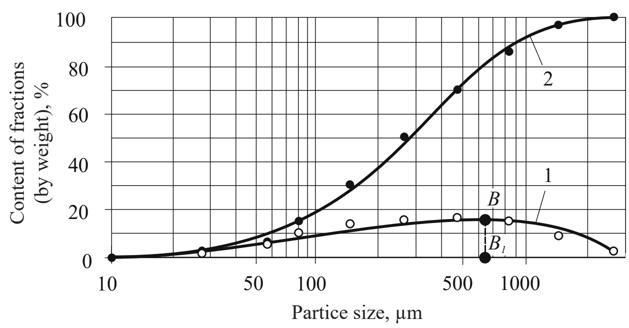


Fig. 13. The distribution of powder particles of maple leaves by sizes: 1 —differential curve; 2 — integral curve

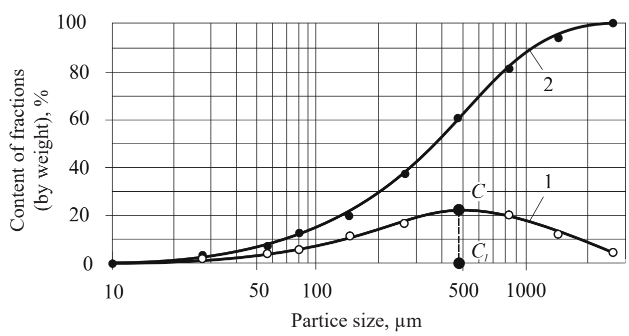


Fig. 14. The distribution of powder particles of oak leaves by sizes: 1 — differential curve; 2 — integral curve

We used a set with a microscope with Sigeta MDC-200 2.0 MP digital camera, a device for transferring of electronic video information to a computer, and a computer with the ToupView 3.7 photographic software to make pictures of dry leaves.

Fig. 15 shows the results of the improvement of the technology of pressing of briquettes of autumn leaves using a new technological scheme of formation of a spherical briquette.

The results of the study made it possible to obtain the regression equation of the density of dry briquettes:

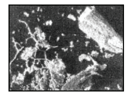
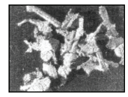
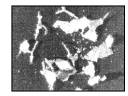
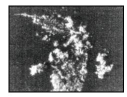
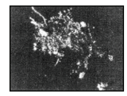
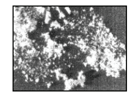
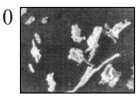
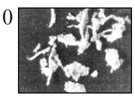
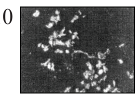
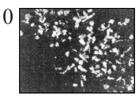
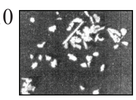
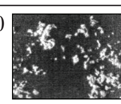
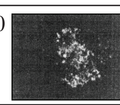
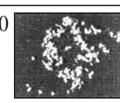
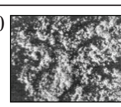
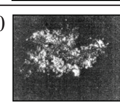
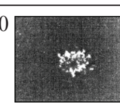
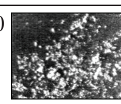
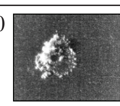
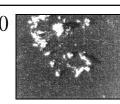
$$y = b_0 + b_1 x_1 + b_2 x_2 = 0.90 + 0.13 x_1 + 0.07 x_2. \quad (9)$$

We obtained a mathematical model of the density of dry briquettes:

$$\rho_d = 0.90 + 0.13 \cdot \left(\frac{\rho_p - 0.23}{0.02} \right) + 0.07 \cdot \left(\frac{\varepsilon - 72.5}{3.5} \right) =$$
$$= -2.045 + 6.5 \rho_p + 0.02 \varepsilon. \quad (10)$$

Table 6

Pictures of particles of dry leaves after grinding and sieving

Fraction, mm	Nutwood leaves	Maple leaves	Oak leaves
–2.500... +1.600	×6 	×6 	×6 
–1.600... +1.000	×6 	×6 	×6 
–1.000... +0.630	×6 	×6 	×6 
–0.630... +0.315	×6 	×6 	×6 
–0.315... +0.160	×10 	×10 	×10 
–0.160... +0.100	×10 	×10 	×10 
–0.100... +0.063	×10 	×10 	×10 
–0.063... +0.050	×10 	×10 	×10 
–0.050... +0.000	×20 	×20 	×20 

a *b* *c*

Fig. 15. Spherical briquettes of dry leaves: *a* — nutwood; *b* — maple; *c* — oak

We checked the hypothesis of the adequacy of the model by the Student's *t*-test [18]:

$$t^{cal} = \frac{|b_0 - \bar{y}_0| \sqrt{N}}{S_y} \equiv \frac{|0.90 - 0.8975| \sqrt{4}}{0.01658} = 0.301, \quad (11)$$

where $\bar{y}_0$ is the arithmetic mean of all repetitions of the central experience; *N* is the number of experiments.

As $t^{cal} < t^{tab}_{\alpha,f} = 3.18$, we do not reject the hypothesis of the adequacy of the model.

We tested the strength of spherical briquettes of dry maple leaves obtained under different technological parameters of pressing and different loading directions:

– briquettes without a body, which would perform the function of reinforcement, obtained without holding under load after pressing: the direction of loading coincided with the direction of pressing;

– briquettes without a body, which would perform the function of reinforcement, obtained without holding under load after pressing: the direction of loading was perpendicular to the direction of pressing;

– briquettes with a body (pinecones), which performed the function of reinforcement, obtained while holding under load after pressing: the direction of loading was perpendicular to the direction of pressing (Fig. 16);

– briquettes without a body, which would perform the function of reinforcement, obtained while holding under load after pressing: the direction of the load was perpendicular to the direction of pressing.

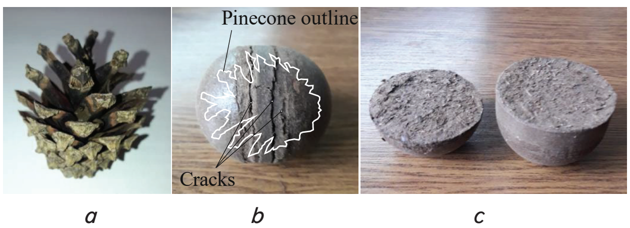


Fig. 16. Before testing spherical briquettes for strength: *a* – pinecone, which performed the function of reinforcement; *b* – briquette with a pinecone and 30-second holding during pressing after the strength test; *c* – briquette with 30-second holding during pressing after the strength test (without a pinecone)

Table 7 gives the results of testing spherical briquettes for strength.

P_p in Table 7 means permissible force, which a briquette must withstand under service conditions (during transportation and storage). One knows from the practice of use that the sufficient mechanical strength of spherical briquettes is 100 N.

The authors of paper [21] propose a new method of pressing spherical briquettes. The process goes with the extraction of compressed air from the matrix capacity through holes in its sidewalls according to the method (Fig. 17). The method makes it possible to increase the strength of spherical briquettes. In addition, the process should occur at the connection of holes in sidewalls of the matrix with a vacuum pump (Fig. 18).

This makes it possible to obtain high-strength spherical briquettes.

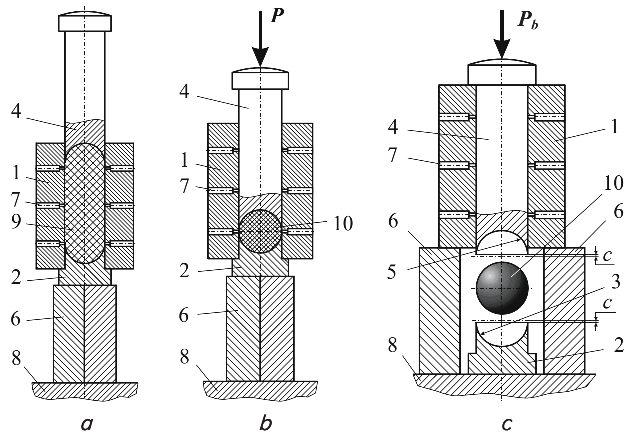


Fig. 17. Scheme of the method of pressing of spherical briquettes with the extraction of compressed air from the matrix capacity through holes in the side walls: *a* – initial phase; *b* – final phase; *c* – moment of ejection of a briquette from the matrix; 1 – matrix; 2 – fixed punch; 3, 5 – hemispherical work surfaces; 4 – movable punch; 6 – two stands; 7 – stepped holes; 8 – table of a hydraulic press; 9 – raw materials; 10 – spherical briquette

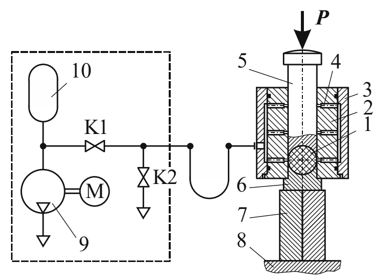


Fig. 18. Scheme of the method of pressing spherical briquettes using a vacuum pump: 1 – spherical briquette; 2 – matrix; 3 – circular sealed chamber; 4 – stepped holes; 5 – movable punch; 6 – fixed punch; 7 – two stands; 8 – table of a hydraulic press; 9 – vacuum pump; 10 – vacuum receiver

5. 2. Results of testing spherical briquettes for burning

We obtained the dependence of t burning temperature on T burning time for each fuel based on the data on fixed current burning temperature (Fig. 19).

Table 7

Test results of spherical briquettes of dry maple leaves for strength

No. of experiment	Technological conditions of pressing		Test results		
	Presence of a body, which performed the function of reinforcement	Duration of holding of a briquette under load, s	Direction of load	Force of destruction (appearance of a crack) P, N	Coefficient of strength factor $n=P/P_p$
1	Without a body	0	Coincided with the direction of pressing	1,500 (a briquette was not destroyed)	15
2	Without a body	0	Perpendicular to the direction of pressing	23	0.23
3	With a body (a pinecone)	30	Perpendicular to the direction of pressing	250	2.5
4	Without a body	30	Perpendicular to the direction of pressing	600	6

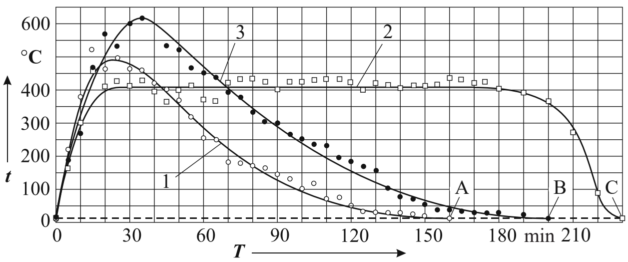


Fig. 19. The experimental dependence of t burning temperature on T burning time: 1 – for firewood; 2 – for RUF briquettes; 3 – for spherical briquettes

A, B and C points correspond to the end time of the burning process, for firewood, RUF briquettes, and spherical briquettes, respectively, in Fig. 19.

6. Discussion of the study results

6. 1. Discussion of the results of improvement of the technology of pressing of briquettes of autumn leaves using a new technological scheme of formation of a spherical briquette

It follows from the results of theoretical studies that the method of pressing proposed by the new technological scheme [12] creates conditions for the formation of a spherical shape briquette in the final phase of pressing. The spherical shape of a briquette, in turn, creates preconditions for quality burning in the initial phase due to free access of air between spherical briquettes into a burning zone.

One can see from the results of the experimental study of particles of dry leaves after grinding (Fig. 12–14) that the distribution of powder particles of different leaves by sizes was not the same. It turns out from the results of the comparative analysis of fractions of powders with the highest content (Table 8) that the powder of oak leaves («peak B» was for a size of 500 μm in Fig. 14) had the smallest particle size, and the powder of nutwood leaves (810 μm) had the largest size. The powder of maple leaves (650 μm) had the average size. It was established that the bulk density of these powder, which was their important characteristic [22, 23], was proportional to the size of the largest content.

The shape of particles (Table 6) in the direction from 2.500 mm to 0.160 mm was flat mainly because of a relatively thin (0.10...0.12 mm) leaf plate of an initial dry leaf, which was ground. The relative rigidity of a particle characterized by the ratio of its length to the thickness of a leaf plate changed in the direction of reduction of particle size from 25 to 1.6. In this size range, there were particles with an irregular broken contour and needle-shaped particles, which passed through round openings of a fixed knife (∅4.5 mm) accidentally. These were mainly the elements of leaf cuttings and capillary thickenings. The shape of particles in the direction from 0.16 mm to 0.00 mm was more volumetric, but it was of incorrect shape and had particles with rigidity, which varied about one. The smallest particles were dust-like.

Fig. 20, *a* shows the degree of influence of factors on ρ_c density of dry briquettes.

It follows from the obtained regression equation (9) that ρ_p bulk density of ground leaves (65 %) has the greatest influence on ρ_c. Its increase leads to an increase in ρ_d density of dry briquettes. Thus, one should consider ρ_p bulk density of ground leaves as the main controlling factor.

The influence of e degree of compression of a briquette (deformation value) is much smaller (35 %), but it is significant. As it increases it leads to an increase in ρ_d density of dry briquettes.

Fig. 20, *b* shows $\rho_d=f(\rho_p, \varepsilon)$ dependence, which demonstrates the influence of factors on ρ_c density of dry briquettes in the chosen factor space of their change. The density of dry briquettes varied from 0.67 to 1.07 g/cm^3 in the experiment (Fig. 15).

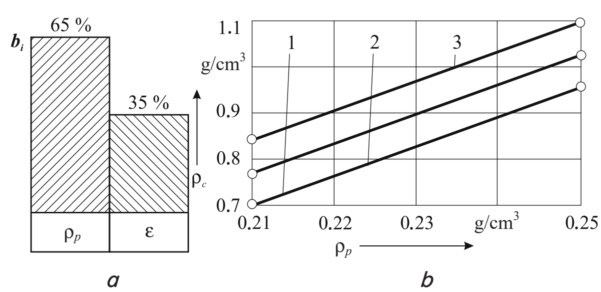


Fig. 20. The dependence of ρ_d density of dry briquettes on ρ_p bulk density of ground leaves and ε degree of compression of a briquette: *a* – degree of influence of factors; *b* – $\rho_d=f(\rho_p, \varepsilon)$ dependence; 1 – ε=69 %; 2 – ε=72.5 %; 3 – ε=76 %

Table 8

Results of comparative analysis of the largest fractions of powders

Powder of:	Initial date		Comparative analysis				
	Wood density, g/cm^3	Bulk density of powder, g/cm^3	Fraction, mm	Content, %	Weight, g	Size of a particle by the largest content	
						μm	%
nutwood leaves	0.64	0.25	−1.000...+0.630	19.87	19.00	810	162
maple leaves	0.69	0.23	−1.000...+0.630	16.2	15.41	650	130
oak leaves	0.75	0.21	−0.630...+0.315	23.48	22.51	500	100

Further increase in the density of dry briquettes is limited by the nominal force of the experimental plant, which is 0.5 MN. In principle, it is possible to obtain briquettes of leaves with a density up to 1.33 g/cm^3, but the optimal density of dry briquettes for use as fuel is 1.0–1.2 g/cm^3 [3].

We obtained the following from the results of the tests of briquettes for strength (Table 7):

– a briquette withstood 1,500 N in the direction of load during pressing and did not break when pressed without a reinforcing body in a briquette and without holding of a briquette under load for a certain amount of time in the final phase. The coefficient of strength factor was n=15. We carried out further tests only for a condition with the direction of load perpendicular to the pressing direction due to a large coefficient of strength factor;

– a briquette broke at 23 N in the direction of load, which was perpendicular to the pressing direction when pressed without a reinforcing body in a briquette and without holding of a briquette under load for a certain amount of time in the final phase. The coefficient of the strength factor was n=0.23. This is unacceptable for the practical application of spherical briquettes. The reason for the destruction of a briquette was the presence of compressed air accumulated in the central plane (a place of greatest convergence of movable and stationary punches, it acted as a compression spring). It took a while for compressed air to escape from a briquette since the one-way gap between the matrix and the punch was very small. It was 0.02 mm;

– we revealed the following at pressing with a body, in particular pinecones, which performed the function of reinforcement, in a briquette and while holding a briquette under load for 30 s in the final phase. The briquette broke at much higher force. It was 250 N in the direction of load, which was perpendicular to the direction of pressing. The coefficient of strength factor was n=2.5. One should note (Fig. 16, *a, b*) that cracks appeared, but a briquette retained its integrity (did not break into pieces) due to «reinforcement»;

– we revealed the following at pressing without a body, which would perform the function of reinforcement, and while holding a briquette under load for 30 s in the final phase. The briquette broke under the even greater force of 600 N in the direction of load, which was perpendicular to the direction of compression. The coefficient of strength factor was n=6. But a briquette broke up into two parts, because of the formation of a crack without «reinforcement» (Fig. 16, *c*).

6. 2. Discussion of the test results of spherical briquettes for burning

The test results of three types of burning fuels, in particular the experimental dependence of t burning temperature on T burning time for firewood, RUF briquettes and spherical briquettes (Fig. 19), implies the following:

– we observed the most intense burning of spherical briquettes of leaves in the initial phase (first 35 minutes). Their burning temperature reached 626 °C. The burning temperature of firewood did not exceed 500 °C and the burning temperature of RUF briquettes was 410 °C. Therefore, the spherical shape of a briquette intensified the initial phase of the burning process by providing guaranteed access of air to the burning zone;

– the temperature distribution after 60 minutes of burning was as follows: firewood – 280 °C; RUF briquettes – 410 °C; spherical briquettes – 470 °C;

– the duration of complete burning of firewood was 160 minutes, spherical briquettes – 200 minutes, RUF briquettes – 230 minutes. Spherical briquettes burn faster in comparison with RUF briquettes because the weight of one spherical briquette (50 mm diameter) was approximately 10 times smaller than the weight of one RUF briquette (155×90×66 mm sizes). This created unequal burning conditions for 1 kg of fuel. A lateral surface area of spherical briquettes, which determined the burning rate, was much larger than a lateral surface area of RUF briquettes. Simple calculations show that we could reach equilibrium if a diameter of spherical briquettes were 114 mm;

– the following percentage of ash was observed: for RUF briquettes – 4 %, for firewood – 5 %, for spherical briquettes made of leaves – 14 %. Paper [24] shows that leaves absorb atmospheric pollution. Therefore, their ash content depends on the environment and, for example, varies from 5.2 to 26.2 % for industrial zones of the city of Gomel. Therefore, it is not possible to control the ash content of burning briquettes of leaves. However, the authors of work [25] showed that biomass burning ash can be useful.

7. Conclusions

1. We proposed a spherical shape of a briquette as the most optimal one to improve the quality of burning, in particular in the initial phase, since even tight packing of balls provides access of air to each individual ball. This is especially important in the initial phase when briquettes touch each other and gain a certain burning temperature. A method has been proposed for pressing the briquettes made from plant waste in a round closed matrix. The method implies that the process occurs during the creation of all-embracing uniform compression with the spherical application of force and with the formation of a ball-shaped briquette in the final phase of the scheme. The method implements a new technological scheme of briquette formation, which makes it possible to compress ground leaves radially and evenly and thereby it provides the same (optimum) conditions for the burning of a briquette in the radial direction from any point of the periphery. We carried out an experimental study of dispersion of particles of dry leaves of nutwood, maple and oak after grinding. It was found that ρ_p bulk density of given powders is proportional to the size of the largest content. We carried out an experimental study of the process of pressing of spherical briquettes of autumn leaves. We obtained a mathematical model of the dependence of ρ_d density of dry briquettes on ρ_p bulk density of ground leaves and ε degree of compression of a briquette (a deformation value). It has been shown that ρ_p bulk density of ground leaves (65 %) has the greatest influence on ρ_c. Its increase leads to an increase in the density of dry briquettes. Thus, one should consider ρ_p bulk density of ground leaves as the main controlling factor. An influence of e degree of compression of a briquette is much smaller (35 %), but it is significant. Its increase leads to an increase in ρ_d density of dry briquettes. The density of dry briquettes varied from 0.67 to 1.07 g/cm^3 in the experiment. It was suggested that the wall thickness in each cross-section of the matrix for pressing of spherical briquettes should be proportional to the compression force by height. It was shown that the matrix with variable wall thickness has less (by 30–35 %) metal content. Therefore, it costs less. It has been shown that the presence of a body, which performs the function of reinforcement, in particular,

a pinecone, in a briquette provides a coefficient of strength factor n=2.5. We tested such a briquette for strength. There were cracks formed, but the briquette retained integrity (it did not break). A cost of a briquette with a pinecone is higher by 10–15 %. It was proven experimentally that one achieves the greatest coefficient of strength factor n=6 in the plane perpendicular to the compression direction under the following conditions. Pressing occurs without a body, which performs the function of reinforcement, in a briquette, and while holding a briquette under load for 30 s in the final phase. A new way for pressing spherical briquettes has been proposed. The method implies that the process occurs at the extraction of compressed air from the matrix cavity through holes in its sidewalls. The method gives the possibility to increase a coefficient of strength factor in 26 times. In addition, the process should occur at the connection of holes in sidewalls of the matrix with a vacuum pump to obtain high-strength spherical briquettes.

2. It has been proven experimentally that there is the most intense burning of spherical briquettes of leaves is in the initial phase. Their burning temperature reaches 626 °C. While the burning temperature of firewood does not exceed 500 °C and the burning temperature of RUF briquettes is 410 °C. Therefore, the spherical shape of a briquette intensifies the initial phase of the burning process by providing guaranteed access of air to the burning zone. Therefore, it is advisable to use spherical briquettes made of leaves as an alternative eco-friendly fuel.

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IMPROVING THE TECHNOLOGICAL PROCESS OF RESTORING THE TILLAGE MACHINE WORKING PARTS

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Проведений аналіз зносу деталей дозволив встановити характерні вимоги технологічного процесу відновлення зношених поверхонь. Експериментальні дослідження по зміцненню робочих поверхонь плужних лемешів дозволили визначити параметри обробки: частота коливань обробного інструменту 1400 хв$^{-1}$, амплітуда коливань 0,5 мм, час обробки 20 с. Дослідження впливу звичайного і вібраційного деформування на характеристики міцності попередньо проводилися на моделях, а потім на деталях. Моделями слугували нові лемеші, експериментальні дослідження на яких забезпечували ідентичність характеру зношування ріжучих елементів. Забезпеченням однакових умов протікання процесів зміцнення дотримувалося однаковість ступеня деформації моделі і деталі.

Достовірність результатів експериментальних досліджень оцінювали відповідно до прийнятого теоретичного закону розподілу при заданій величині ймовірності α=0,95. Дослідженнями встановлено, що найбільшій ймовірністі 0,39 відповідає ширина лемешу 116–117,5 мм, яка має певний вплив на працездатність лемешу.

Експериментально встановлено, що ступінь зміцнення лемешів зі сталі Л-53 з подальшим наплавленням сормайтом і вібраційним зміцненням в 1,85 рази більше, ніж при звичайній обробці. Проведені дослідження дозволили визначити характер зміни форми лемешу і товщини різальної кромки, а також вибрати більш ефективний технологічний процес його відновлення методом вібраційного зміцнення. Запропоновано метод відновлення лемешів приварюванням шин зі сталі 45 з автоматичним наплавленням сормайтом і подальшим вібраційним зміцненням

Ключові слова: деформування, динаміка зношування, вібраційна обробка, зносостійкість поверхні

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1. Introduction

One of the problems of repair activities is to increase the durability of working parts of tillage machines during their restoration. A solution to this problem will allow repair enterprises to reduce downtime, improve the quality of maintenance and repair and improve indicators of equipment reliability and utilization [1].

A significant role in ensuring the long service life of tillage machines is assigned to the development and application of progressive technological processes which will significantly improve indicators of restoration quality.

The feasibility of the restoration of working parts of these machines is to reduce repair costs by cutting expenses on new spare parts and operation costs [2].

In this regard, the technical condition of working parts of the tillage machines significantly affecting the yield of agricultural crops is of particular interest.

When restoring parts, it is necessary to ensure their quality at a level of new parts or even higher. Wear resistance of