ГАЛУЗЕВЕ МАШИНОБУДУВАННЯ

UDC 633.584.3 046.67
DOI https://doi.org/10.32838/2663-5941/2019.3-1/03

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SCIENTIFIC AND TECHNICAL ASPECTS OF GRANULATION OF ENERGETIC WILLOW TREE

Areas of production of biofuels from energy willow are considered. The perspective type of granulator with a ring matrix is determined. The processes of granulation of the willow mass are investigated. The analysis of a complex of machines for the production of fuel pellets from energy willow is carried out. The expediency of processing of willow mass in fuel pellets on the equipment of domestic production is proved.

Key words: *energetic willow tree, biopowered granules, processes, calculations, granulator, equipment.*

Formulation of the problem. Until a certain time, fuels from different types of biomass did not compete with subterranean resources, in particular natural gas, oil, and coal. At present, the spread of biofuels induced by the problems of environmental protection, rising prices of subterranean energy sources [1, p. 68].

In order to achieve the status of energy independence of the country, the National Security and Defense Council of Ukraine dated April 28, 2014 adopted a decision “On the state of ensuring energy security in connection with the situation regarding the supply of natural gas to Ukraine”, where the government will implement the provisions of the Energy Strategy for the period until 2030 in order to develop renewable energy sources, including fuels from secondary biomass and energy crops. The Bioenergy Association of Ukraine has developed a concept [1, p. 69; 2, p. 4], according to which in 2030 energy crops are expected to produce 9.2 million tons of fuel equivalent. In Ukraine, unprocessed areas can grow fast-growing energy crops, for example, in areas up to 1 million hectares of energy willow (Salix), poplar (Populus), Miscanthus, etc. [2, p. 5].

Usually, the willow mass is crushed to a state of 10–70 mm of wood, dried up to 30–35% and sent to a boiler house, where the heat of combustion is about 12 MJ/kg. However, it is proved that for the effective combustion of biomass it is necessary to have dense products of the same shape and size to increase the contact of surfaces with air, increase the heat transfer and process automation in heating systems. Such energy conversion is realized by using biofuel pellets and briquettes [2, p. 7; 3, p. 18].

At the same time, in the scientific papers and others concerning granulation of biomass, features of obtaining pellets from energy willow are not considered. The introduction of solid fuel production is often complicated by the limitation of their technical equipment. Therefore, there is a need for a more in-depth analysis of these problems.

Analysis of recent research and publications. Energy willow is a chimney-shaped with a short growing period (shore rotation tree). It is characterized by a high growth of the length of the stem (1.2–1.5 m/year), with a humidity of 12–15% gives a heat output of 18 MJ/kg, and also has a low chlorine content of $< 0.1\%$, a relatively low ash content $\approx 1.9\%$, high melting point of ash $> 1500°C$, which minimizes the smelting and corrosion of the surfaces of the boiler equipment [3; 4].

Of the known species of willow (basket, white, grey, crack, goat, eared, almond, purpura, etc.), for the needs of energy are more often grown basket willow (Salix Viminalis) [4, p. 27].

The willow mass is harvested, as a rule, every 3 years with a forage harvester with a harvester for willow or special machines in the period from November to April at a humidity of about 50% [4, p. 28]. The one-step method of harvesting is to cut the willow with its simultaneous grinding, loading cod into vehicles. For the implementation of such technology, combines with productivity of up to 30 t/h are used by Claas, New Holland and

Krone, as well as machines for harvesting sugar cane with modified cutter machines. The two-stage method consists of two technological phases: during the first phase the plants are cut, while the second one is crushing. In some technologies, willow after cutting is pressed into packs for further processing [5, p. 230].

Typically, pellet granules with circular or flat matrices are used to obtain fuel pellets from biomass. The rotary rollers form the tension contact of the consolidation of the raw material on the surface of the matrix and push it through the ducts of the matrix under a pressure of up to 40 MPa [6, p. 252].

During the formation of granules in the matrix there are phenomena of intense friction and dry extrusion. As a result, the temperature rises to 100°C, and the lignin, contained in the raw material, glues particles in a density of up to 1200 kg/m^3 granules and promotes the formation of a protective film on the surface of products [7, p. 95].

The purpose of the research is to increase the efficiency of the production of granular fuel from energetic willow in conditions of agrarian enterprises by studying the process of granulation and selecting a rational complex of technological equipment.

Research results. The comparative analysis of granulation processes shows that for the production of wood biomass pellets, including from willow, the working bodies of the machine operate with increased loads and have constructive differences, namely: reinforced granulation unit, two-stage V-belts or gearbox transmission, forced loading raw materials for even distribution on rollers, etc.

In Ukraine, the engineering group ICK Group TM GRANTECH takes the leading position in the design and production of technological equipment for the production of biofuel and feed pellets [6, p. 253; 7, p. 98]. According to the results of the analysis, it is established that the most promising granulation tool for the typical production line of biofuel granules on the basis of agrarian enterprises is a press granulator model ГТ-304/55 Д with a ring matrix (Fig. 1).

The task of these researches involves the development of a methodology for calculating the main parameters of the granulation node. The maximum axial compression pressure of biomass P_{max} in the working area of the matrix on the curve ***aA*** (Fig. 2) is determined by the formula [7, p. 96]:

$$P_{max} = C\left(e^{a(\rho_{max}-\rho_0)} - 1\right), \qquad (1)$$

where P_{max} – maximum axial pressure during granulation, MPa; C – parameter of the material, which determines the resistance of the compression mass, MPa; a – the parameter of the material, which depends on its structural and mechanical properties, m^3/kg; ρ_{max} – the highest granulation density, kg/m^3 ($\rho_{max} = k_{щ}\,\rho$, where ρ is the specified density of the granule, $k_{щ}$ – the density coefficient for the granules is equal to 1.1–1.4; ρ_0 – initial density of wood biomass, kg/m^3.

The pressure, determined by the formula (1), acts on the pushing stage and depends not only on

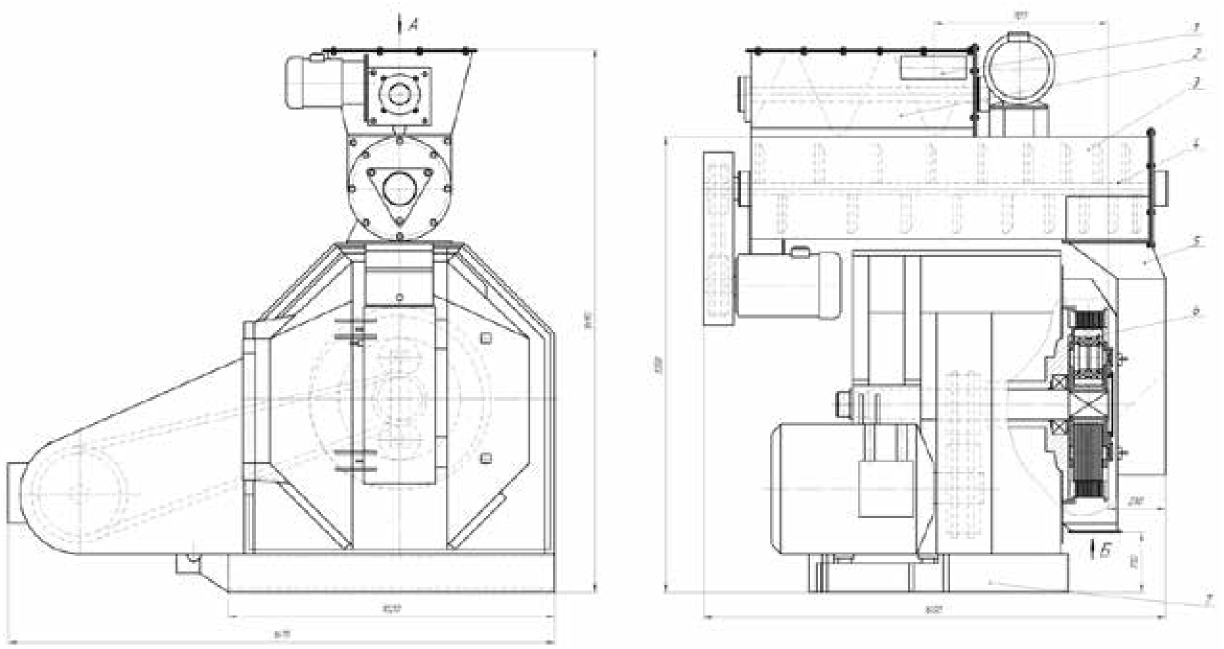


Fig. 1. General view of the perspective granulator ГТ-304/55 Д: 1 – body of the feeder; 2 – feeder-dispenser; 3 – body of the mixer; 4 – mixer; 5 – channel of supply of raw materials; 6 – point of granulation; 7 – frame

the counter pressure in the fillets, but also on the perforation coefficient of the matrix, therefore $P_{max} = P_{отв}\left[1+\frac{2}{3}(1-k_n)\frac{f}{\xi\, tg\alpha_n}\right]$, where $P_{отв}$ – counterbalance of granules in the openings of the matrix, MPa; k_n – coefficient of perforation of the matrix; $k_n = 0.45–0.55$; ξ – lateral pressure coefficient; α_n – angle of the jumper between the holes of the matrix, degrees.

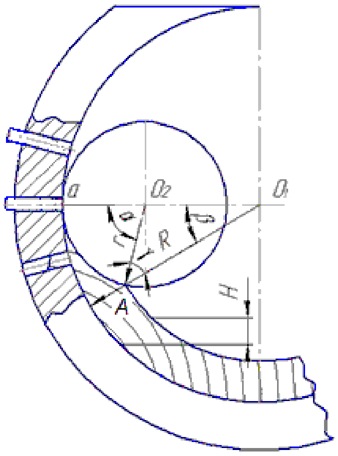


Fig. 2. Scheme to calculate parameters of the process of obtaining granules in a ring matrix

The area of the working surface of the matrix $S_м$ on the condition of providing strong bonds in the fuel pellets is calculated by the formula [7, p. 97]:

$$S_м = \frac{q_{пв}\, t_{бм}}{k_n\, L\, \rho_{отв}}\lambda, \tag{2}$$

where $q_{пв}$ – bandwidth of the compression knot, kg/s; $t_{бм}$ – time of raw material biomass in filer, c; at the granulation of wood biomass $t_{бм}$ = 16–18 s; L – length of the technological opening (filer) of the matrix, m; $\rho_{отв} = (0.92-0.96)\,\rho_{max}$ – the density of the granule at the exit from the matrix channel, when there is some expansion of the material and a decrease in its density, kg/m^3; λ – a coefficient that takes into account the uneven distribution of raw materials on the surface of the matrix. The value of λ is determined by the design of nutritional devices, for example, when using screw feeders λ = 1.1–1.6, lobed – λ = 1.5–2.5.

The number of filers in the matrix is determined in this way: $z_0 = \frac{S_м}{S_{отв}}$.

The height of the biomass layer H in the zone of its capturing by the roller, proceeding from the triangle AO_1O_2, is preliminarily calculated according to the formula [7, p. 98]:

$$H = R - \sqrt{r^2 + (R-r)^2 + 2r(R-r)cos\alpha}, \tag{3}$$

where R and r are the radii of the matrix and roll, m (see Fig. 2); α – angle of pressing.

In the absence of towing between the roller and the matrix of the arc of the rotation in the capture zone AB will be equal, that is, $\cup\alpha r = \cup\beta R$, hence $\frac{\alpha}{\beta} = \frac{r}{R}$, and angle $\beta = \frac{\alpha r}{R}$. From the triangle AO_1O_2 we see that $\pi = (\pi-\alpha)+\beta+\gamma$, and $\alpha = \beta+\gamma$. Consequently, the angle $\gamma = \alpha - \beta$ or $\gamma = \alpha\left[1-(r/R_м)\right]$.

To capture and compress the bulk wood biomass with a roller, it is necessary to have the angle between the radii of the roller (AO_2) and the matrix (AO_1) carried out through the capture point A does not exceed the friction angle of the biomass (φ = 25–39°) on the surface of the roller. Consequently, the condition $\gamma \le \varphi$ must be satisfied. Then the pressing angle α is determined from the condition:

$$\alpha \le \frac{\varphi}{\left[1-\left(\frac{r}{R}\right)\right]}. \tag{4}$$

The need for a compact placement of the pressing rolls leads to the fact that the ratio between the radii of rollers and the matrix (r/R) varies within narrow limits. In designs with two rollers r/R = 0.42–0.45, with three – 0.4–0.42.

Taking into account the obtained data, an expression was found for calculating the height of the biomass layer H:

$$H = R[1-\sqrt{1-\frac{2r}{R}\left[1-\left(\frac{r}{R}\right)\right](1-cos\alpha)}]. \tag{5}$$

Width and radius of roller granulator conditioned by technical and technological parameters. In connection with this, the ratio ψ of the width of the roller to its radius r, as a rule, is 1.0–1.6. Assuming that the width of the roll is equal to the width of the matrix, the radius of the matrix is determined:

$$R = \sqrt{\frac{S_м}{2\pi\psi}}. \tag{6}$$

The rotational speed of the matrix n (c^{-1}) is determined by the condition $n_{min} < n_m < n_{max}$:

$$n_{min} = \frac{1}{2\pi}\sqrt{\frac{g}{R\,sin\varphi}}, \quad n_{max} = \frac{1}{2\pi}\sqrt{\frac{\sigma_p}{R_н\, b_ф\, d\, \rho}}, \tag{7}$$

where g – acceleration of free fall, m/s^2; σ_p – the destructive tension of separation in biomass of the filers, Pa; $R_н$ – external radius of the matrix, m; $b_ф$ – ratio of the length of the filers to its diameter d.

The average biomass displacement rate in a filer is determined by the formula:

$$v_{cp} = \frac{L}{t_{бм}} = \frac{p_{max}S_{отв}}{(F_{cm}\,\xi\, P_{отв}\, p_к\, t_{бм})}. \tag{8}$$

The productivity of a granulator $Q\left(\frac{m^3}{h}\right)$ with a ring matrix is determined by the formula [7, p. 101]:

$$Q = 2\pi\, b\, \rho\, z_в\, R^2 \beta\,(1-\beta)\left(1-\cos\frac{\gamma}{\beta}\right)\omega\,, \qquad (9)$$

where b – the width of the woody biomass layer that is granulated, m; ρ – biomass density, kg/m^3; $z_в$ – number of pressing rolls, pieces; β – the ratio of the radii of the press roll to the matrix; γ – angle of natural slope of woody biomass, degree; ω – angular velocity of rotation of rollers, c^{-1}.

The power of Nгр for the granulation process is determined by the formula:

$$N_{гр} = 10^{-3} F_{тр} v_{ср}\, z_ц\,, \qquad (10)$$

where $z_ц$ – the number of openings in which the granulation proceeds simultaneously on the arc of the capture zone ($z_ц = \frac{z_0\, z_в\, \alpha}{360}$, where $z_в$ – number of compression rollers).

The *N* power to the granulator drive, without taking into account the drive of servicing mechanisms (feeder, dispenser, mixer, etc.) is determined by the formula:

$$N = \frac{\left(N_{гр} + N_{x.x}\right)}{\left(\eta_{тр}\,\eta_{дв}\right)}, \qquad (11)$$

where $N_{x.x}$ – power of the granulator idling, kW; $\eta_{тр}\, i\, \eta_{дв}$ – efficiency of transmission and electric motor at nominal load.

It is important to choose the length of the granulation channel to obtain granules of a given density. When pushing biomass in a filer, friction force $F_{тр}$ occurs, which is defined as follows:

$$F_{тр} = f_{ст} N = f_{ст}\,\tau\, S_б = f_{ст}\cdot\tau\cdot p_п \cdot L =$$
$$= f_{ст}\cdot\xi\cdot P_{отв}\cdot p_п\cdot L\,, \qquad (12)$$

where $f_{ст}$ – static coefficient of friction of wood biomass; *N* – force of normal reaction, H; τ – tangential tension from the lateral pressure in the filer, Pa; $S_б$ – area of the lateral surface of the filers, m^2; $p_п$ – perimeter of the cross-section of the filers, m; ξ – lateral discharge ratio; ξ = 0.4–0.45; $P_{отв} = (0.1-0.4)\,P_{max}$ – counterbalance of granules in the openings of the matrix, kPa; L – length of the filers matrix, m.

Taking into account formula (12) and the prerequisite for friction, the value of the length of the matrix's technological opening must correspond to the following condition:

$$L \ge P_{max}\, S_б \,/\, (f_{ст}\, \xi\, P_{отв}\, p_п)\,. \qquad (13)$$

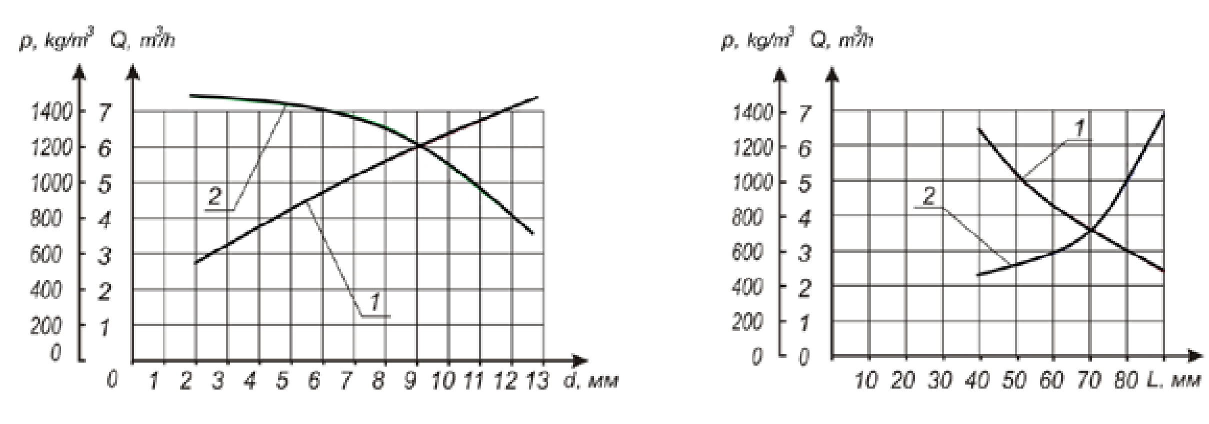
When pushing biomass into pellets, the relaxation of the stresses will end. Otherwise, due to the elastic aftereffect of the granule, when exiting the matrix, it will substantially expand and have insufficient strength. Taking into account the given productivity, the average rate of movement of the pellet over the filament $\upsilon_{ср}$, determines the length of the channel $L_{рел}$ under the relaxation conditions:

$$L_{рел} = \upsilon_{ср}\, t_{рел}\,, \qquad (14)$$

where $t_{рел}$ – the required period of pelleting time in the filer for relaxation, s.

Consequently, for the effective implementation of the process of forming fuel pellets, the constructive length of the matrix filer should correspond to the following condition: $L \ge L_{рел}$.

The analysis shows that the main factors of the parameters of the granulation node are the diameter *d* and the length *L* of the matrix opening, the coefficient of friction $k_{тр}$ of biomass about the inner surface of the filer. Several factors are secondary, in particular the diameter of the roller D_p, the angle of the chamfer *α*. According to the results of the research, graphic dependences of the process criteria on the size of the apertures of the matrix were constructed (Fig. 3).



a) b)

Fig. 3. Dependences of the productivity Q of the granulator (1) and the density of the granules ρ (2) on the parameters of the channel of the matrix: a – diameter d; b – length L

The best-known experience of California Pellet Mill [6, p. 167] suggests that when the diameter of the die is from 6 mm to 8 mm (this is the most common diameter of the pellet), the length of the forming part of the channel should be 40–45 mm. Moreover, the quality of the granules with a diameter of 6 mm is higher than 8 mm.

The analysis of technology for the production of fuel pellets from willow chips has allowed to determine the main processes, namely: drying up to 10–12%, final grinding to sawdust 1–5 mm, granulation, cooling from ≈100°C to ≈40°C, sifting, warehousing.

For agro-industrial complex it is expedient to use flexible mini-lines with the composition of domestic machines for the production of granular biofuels, which ensure implementation of fuel potential and needs of the economy in thermal energy. The well-known scheme of the technological line (Fig. 4) envisages introduction of modern technologies of willow pelleting on the basis of agricultural enterprises. In the design process, favorable technological aspects are determined according to certain technical and economic criteria. For the production of 1 ton of fuel pellets 4–5 m^3 of willow mass in the form of chips of natural moisture is required.

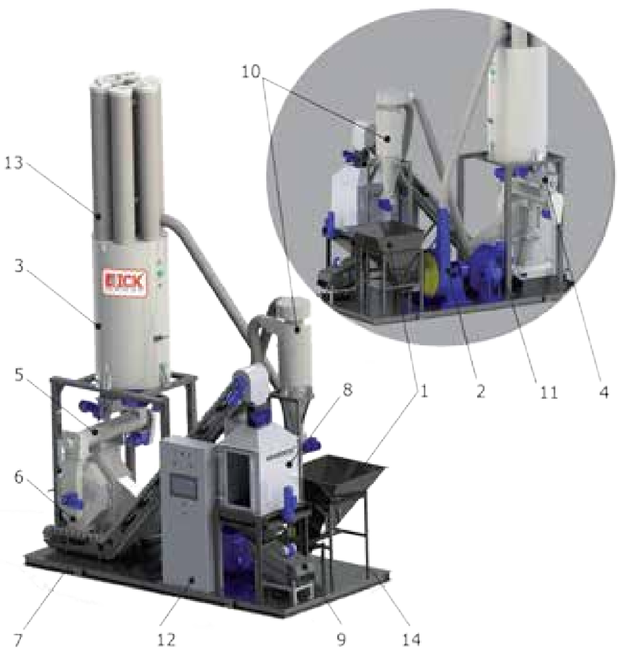


Fig. 4. Technological scheme of the mini-line production of fuel pellets from energetic willows: 1 – receiving hopper; 2 – hammer crusher; 3 – intermediate bunker; 4 – dispenser; 5 – mixer; 6 – press granulator ГТ-304 Д; 7 – belt conveyor; 8 – cooler ГТО-0.6; 9 – vibration sieve ГТП-1; 10 – cyclone; 11 – fan; 12 – control panel; 13 – filters; 14 – platform

Willow cod from the storage place is delivered to a convection dryer, which may be type of tape, drum (for example, series СБУ-1.5), sectional shovel (for example, series ГТСК-0.6 of the firm ICK Group TM GRANTECH), etc. The advantages of domestic dryers are simplicity of design, versatility and reliability in work. For the process of drying, is used a mixture of air with flue gases from 150°C to 300°C, which are released when burning pellets of their own production.

The crushing of cod is carried out in a hammer crusher (for example, ГТДРМ -0.7, КДУ-2, ДМ-Ф-1, ДМБ-М) from the sizes of 20–70 mm to the size of sawdust particles of 1–5 mm. The effectiveness of the subsequent granulation process depends on the fractional composition of the raw material. In the hammer crushers, the degree of grinding is very high (reaches 20–30), and the specific energy consumption for crushing is lower than in other types of crushers. Hammer crushers differ in simplicity of construction, high productivity, lower in 3–5,5 times the cost per unit of output than in roller crushers. In hammer crushers, the power of an electric motor is lower by 14–27%.

Granulation of the prepared willow mass is carried out using a press granulator of the model ГТ-304/55 Д with a ring matrix, investigated in this work. In the openings of the matrix under the action of biomass rollers, it is sealed under high pressure up to 40 MPa. Also, in the formation of granules there are physical phenomena of dry diffusion, which are accompanied by intense friction. As a result, the temperature rises to 100°C, which provides the separation from wood biomass lignin, which serves as a connecting agent and glues particles in densely packed up to 1200 kg/m^3 fuel pellets and contributes to the formation of a protective film on their surface. Then soft and hot granules are directed to the cooling process [6, p. 168; 8].

For the possibility of transportation and storage, the pellets are cooled to 40°C with air in countercurrent coolers (for example, a ГТО-0.6 series). During cooling, lignin hardens on the surface of the granules, which gives them strength and contributes to the preservation of the shape.

Further, the granules are sifted on the vibration sieve (for example, a series of ГТП-1) to separate the fine fraction and non-liquid materials, which are returned to re-granulate or used as fuel in the heat generator of the dryer. Suitable fuel pellets are sent to the warehouse of finished products [8].

Conclusions. 1. Taking into account the scientific and production achievements of foreign leading companies in the field of solid biofuel bioenergy and the fuel potential of energy crops in Ukraine to 9 million tons, the expediency of introducing production of fuel pellets from energy plantations, including fast growing varieties of willow, poplar, acacia etc., for obtaining heat and power autonomy at the regional level.

2. The analysis of technologies of cultivation and harvesting of energetic willow varieties, such as Salix Viminalis, Salix Wilhelm, Salix alba, confirms the effectiveness of this direction of domestic agricultural machinery, including in the climatic zones of the forest-steppe and the northern steppe zone. The fuel value of energetic willow does not cause doubt, namely: the calorific value of fuel granules from the willow mass at a humidity of 10–12 % reaches 18 MJ/kg; low chlorine content < 0.1%, low ash content ≈ 1.9%, high melting point of ash > 1500°C make insignificant slipping and corrosion of surfaces of heating installations.

3. Advantages of fuel pellets from energetic willow relative to traditional types of fuels:

– differ from the firewood with greater dryness (8–12% versus 20–40%) and the density of products (over 1000 kg/m^3), which provides a higher calorific value to 18 MJ/kg against 10–15 MJ/kg;

– do not smell unlike subterranean types of fuel;

– do not self-ignite when temperatures rise, not explosive;

– high bulk density (about 650 kg/m^3) of granules does not require large areas, and the volume under pellets is five times smaller than that of cod, with the same heating;

– the efficiency of the effective pellet boiler reaches 90%, which is significantly higher than coal (up to 75%) and wood – 40–50%;

– due to the small size, uniform shape, thickness and consistency of products, the processes of loading, mixing and combustion of fuel pellets are subject to automation, and the stability of their properties contributes to the exact dosage in heating installations;

– in emissions from burned granules virtually no sulfur, and carbon dioxide emission is lower in 10–50 times than in other types of solid fuel;

– the ash remaining in the pellet combustion is used as fertilizer;

– in the production of willow pellets, about 20–28% of electricity is consumed from their heat and energy output;

– fuel pellets are renewable environmentally friendly products, and the ever-rising energy sources of the subsoil have a limit to exhaustion.

4. It has been determined that for granulation of the prepared willow mass it is expedient to use devices with circular or flat matrices. The granular nodes of the matrix type relate to mechanisms of continuous action. The technically positive aspect of the nodes is the absence of an idling speed of the actuators and their work at steady speeds, which leads to minimal action of inertial forces. A comparative analysis of rotary matrix press rollers, in particular such firms as CPM Europe (the Netherlands), Munch, Salmatec (Germany), GENERAL DIES (Italy), ICK Group TM GRANTECH (Ukraine–Germany), OGM (Lithuania), etc., indicates that the promising granulation tool for the production of pellets from the willow mass in the economy is domestic granulator model ГТ-304/55Д with an approximate productivity of 500 kg/h, used as an object for studying the granulation process.

5. Increasing the pressure up to 40 MPa when biomass propagates through the matrix openings strengthens the granules by eliminating air pores and voids, as well as increasing the area of contact between the particles, which results in the growth of molecular adhesion forces. After gaining granules without porous state, further increase of pressure becomes ineffective. The strength of the granules increases with the increase in the duration of extrusion, that is, the length of the filter must meet the condition: $L \geq L_{рел}$. The quality of the pellets depends on the degree of grinding and moisture of the willow mass.

It is determined that the main factors of the parameters of the granulation node are the diameter d and the length L of the matrix opening, the coefficient of dry friction mass on the inner surface of the filer. According to the results of the research, graphic dependences of the main criteria of the process on the dimensions of the matrix apertures are constructed.

6. According to the analysis of technological lines, it was determined that for the production of fuel pellets from energy willow in the conditions of the economy it is expedient to use universal lines of low power up to 1 t/year equipped with a set of equipment of the domestic manufacturer. High efficiency indicators were obtained during operation of the mini complex for granulating ГТЛ-304 of ICK Group TM GRANTECH. Basic equipment of the complex: receiving hopper; crusher ГТДРМ-0.7; press granulator ГТ-304/55Д; cooler ГТО-0.6; sifter ГТП -1; control system. Productivity of the line up to – 500 kg/h, specific energy consumption – 390–420 Joule per 1 kg of pellets, the required production space for the complex is 11 m2 (5.0 x 2.2) m [8].

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НАУКОВО-ТЕХНІЧНІ АСПЕКТИ ГРАНУЛЮВАННЯ ЕНЕРГЕТИЧНОЇ ВЕРБИ

Розглянуті напрями виробництва біопалива з енергетичної верби. Визначено перспективний тип гранулятора з кільцевою матрицею. Досліджено процеси гранулювання вербової маси. Проведено аналіз комплексу машин для виробництва паливних гранул з енергетичної верби. Доведена доцільність переробки вербової маси у паливні гранули на обладнанні вітчизняного виробництва.

Ключові слова: *енергетична верба, біопаливні гранули, процеси, розрахунки, гранулятор, обладнання.*

НАУЧНО-ТЕХНИЧЕСКИЕ АСПЕКТЫ ГРАНУЛИРОВАНИЯ ЭНЕРГЕТИЧЕСКОЙ ИВЫ

Рассмотрены направления производства биотоплива из энергетической вербы. Определен перспективный тип гранулятора с кольцевой матрицей. Исследованы процессы гранулирования вербной массы. Проведён анализ комплекса машин для производства топливных гранул из энергетической вербы. Доказана целесообразность переработки вербной массы в топливные гранулы на оборудовании отечественного производства.

Ключевые слова: *энергетическая ива, биотопливные гранулы, процессы, расчеты, гранулятор, оборудование.*