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INNOVATIVE APPROACHES TO THE USE OF BIOGAS TECHNOLOGY PRODUCTS

Disposal of organic waste from animal husbandry, in particular from poultry, in the conditions of Vinnytsia region, which has favorable conditions for agriculture and processing industry, remains an urgent problem. Traditional processing technologies do not provide effective disinfection and deodorization of waste, which limits the possibilities of their use as fertilizers. The implementation of energy-saving waste disposal and decontamination systems allows to increase significantly the economic efficiency of agro-industrial enterprises and reduce environmental risks.

Special attention is paid to the bioconversion of organic substances by means of anaerobic fermentation, which makes it possible to obtain biogas with high economic efficiency. Methane fermentation is characterized by a diverse species composition of microflora, which contributes to the adaptation of the process to changes in raw materials. At the same time, in the conditions of Ukraine, it is necessary to use high-tech approaches to optimize biogas plants, taking into account climatic and economic features. The work analyzes the methods of increasing the efficiency of BSU work. In particular, it is proposed to improve the systems of thermostabilization, mixing of the substrate, and utilization of the heat of the fermented material. The main technological aspects of mixing the substrate, which is a critical factor in the stable operation of the reactor, are considered.

Effective mixing ensures: Prevention of the formation of crust and sediment, which reduce the volume of the reactor core. Uniform distribution of temperature and bacterial population in the reactor. Intensification of biogas release from the layer of the substrate.

On the basis of the conducted research, it was concluded that regular stirring every 4-6 hours allows to increase the yield of biogas by 50%, while excessively frequent stirring can negatively affect fermentation. It is recommended to adapt the frequency of stirring and the choice of the type of stirrer to the specific operating conditions of the reactor. The obtained results can be used for the design and modernization of biogas plants, which will contribute to increasing the energy efficiency of agro-industrial enterprises and the development of alternative energy.

Key words: *biogas plants, substrate mixing, methane fermentation, energy efficiency, alternative energy, waste disposal, biogas output.*

Formulation of the problem. In the modern conditions of agro-industrial production in Vinnytsia, as well as in other regions of Ukraine, the disposal of organic waste from animal husbandry is one of the key environmental and technological problems. A significant amount of such waste, particularly in poultry farming, requires efficient processing with minimal impact on the environment. Traditional disposal methods do not provide proper disinfection, deodorization and preparation of organic fertilizers, which limits their economic efficiency and environmental safety. Biogas plants (BGU), which are used to process organic waste to produce biogas, have significant potential in solving this problem. However, their efficiency often remains low due to the imperfection of technological systems, in particular mixing of the substrate, thermostabilization and utilization of the heat of the fermented material. This leads to uneven fermentation, sludge formation, reduced biogas yield and overall profitability of the plants [1]. An additional complication is the dependence of technological processes on climatic conditions, which is especially relevant for Ukraine. Compared to Western Europe, where the problems of waste disposal are solved thanks to high-tech approaches and state support, in Ukraine it is necessary to improve BGU technologies to ensure their economic feasibility and environmental efficiency [2; 3]. Thus, in order to increase the profitability of BSU work, there is a need to: optimize the substrate mixing system to prevent the formation of a crust and sediment, ensure even distribution of temperature and bacterial population; improve systems for utilization of the heat of the fermented substrate to increase energy efficiency; adapt the operating modes of the installations to seasonal changes to ensure the stability of the fermentation process. Solving these issues is critically important for increasing the efficiency of biogas technologies, developing alternative energy and reducing the environmental burden [4, 5].

Analysis of the latest research and publications. Today, biogas technologies have undergone significant development, in particular in the aspect of innovative use of anaerobic fermentation products. European experience demonstrates the effectiveness of biogas plants in the processing of agricultural and industrial waste, municipal organic waste and sewage sludge, which contributes to the sustainable use of renewable energy sources [4].

According to the analysis of the European Biogas Association (EBA), production of bioga and enriched biogas (biomethan) is developing in Europe. Combined biogas and biomethane production in 2023 amounted to 234 TWh or 22 bcm. Thisis the consumption of Belgium, Denmark and Ireland altogether or 7% of the natural gas consumption of the EU in 2023. 25 European countries are actively involved in biomethane production. There are currently 1,510 biomethane plants operating in Europe, of which 1,324 are in the EU-27. Over 85% are connected to the gas network (mainly distribution networks) [6].

In Ukraine, there is also a growing interest in biogas technologies. In particular, the MHP company is implementing the innovative program "Biogas 5.0" with the aim of achieving carbon neutrality of production [7]. This project involves the use of biogas plants for the processing of poultry waste, which not only reduces the environmental burden, but also ensures the production of renewable energy.

Modern research is also focused on increasing the efficiency of biogas plants through the optimization of fermentation processes and the use of different types of raw materials [8-10]. In particular, the methods of preliminary preparation of raw materials that increase the yield of biogas are studied, as well as technologies for enriching biogas to biomethane for further use in energy systems.

At the same time, there are certain barriers to the development of biogas technologies in Ukraine, including the lack of a state support program and insufficient funding. Researchers emphasize the need to focus on own developments in the field of biogas technologies and state support to ensure their profitability [11].

In general, modern research 1and publications testify to the significant potential of biogas technologies in solving energy and environmental problems. Innovative approaches to the use of biogas technology products, such as biomethane production and the use of digestate as fertilizer, contribute to sustainable development and the transition to renewable energy sources.

The purpose of the study. Increasing the efficiency of biogas plants (BGU) by improving the mixing, thermostabilization and utilization of heat of the fermented substrate to ensure a stable fermentation process, increase the biogas yield and reduce the release of waste into the environment..

The main results of the study. Mixing methods (Fig. 1). Raw materials can be mixed in several main ways: with the help of mechanical stirrers, by passing biogas through its layer, or by pumping raw materials from the upper zone of the reactor to the lower one. Mechanical agitators are usually equipped with working elements such as augers, paddles or bars, which can be operated manually or by a motor. [2].

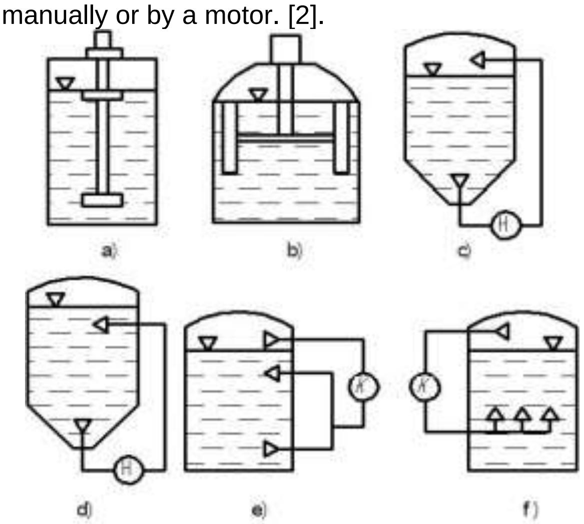

Fig. 1. Raw material mixing systems for vertical reactors: a, b – mechanical stirrer; c, d – with the help of a pump; e – biogas and liquid; f – biogas

Mechanical mixing (Fig. 2. b,c,e).. This method is widely used in horizontal steel reactors.

In such installations, a horizontal shaft passes through the entire length of the reactor, and blades or tubes curved in the form of loops are attached to it. During the rotation of the shaft, these elements ensure the mixing of raw materials.

Mechanical stirrers with a manual drive are distinguished by ease of manufacture and operation. They are used in reactors of small biogas plants with a low level of productivity. Their main task is to destroy the crust and redirect the sediment to the outlet.

The design of the stirrers involves a horizontally or vertically located shaft inside the reactor, parallel to its central axis. Blades or other elements with a helical surface are attached to the shaft, which ensure the movement of the mass, enriched with methane bacteria, from the loading zone to the unloading zone. This helps to accelerate the process of methane formation and shortens the time the raw materials stay in the reactor.

Hydraulic mixing (Fig. 2, d). is carried out with the help of a pump, which ensures complete mixing of raw materials simultaneously with loading and unloading. Pumps are usually installed in the center of the reactor, which allows you to perform additional functions necessary for the stable operation of the system.

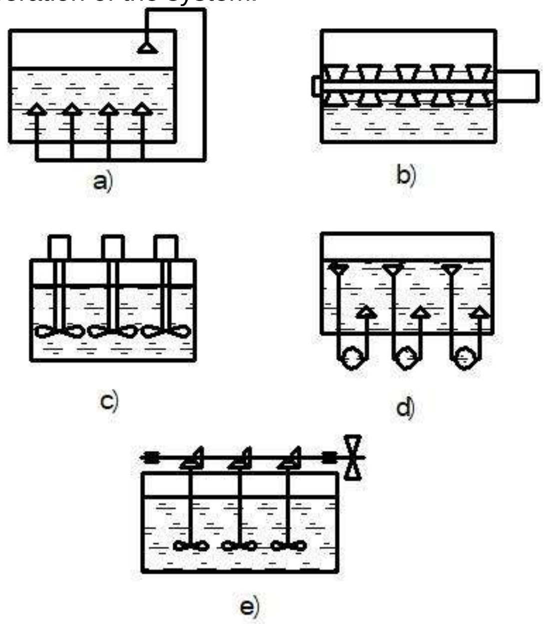

Fig. 2. Raw material mixing devices for horizontal reactors: a – biogas; b – mechanical blades; c – mechanical stirrers with electric motors; d – with the help of a pump; e – mechanical stirrers from a wind engine

Pneumatic mixing (Fig. 2, a).occurs by recirculating the separated biogas back into the reactor through a piping system mounted on the bottom. This method ensures delicate mixing of raw materials. The main problem with these systems is the risk of raw materials entering the gas network, which can be avoided by installing a valve system to prevent backflow.

Mixing, which is carried out by recirculating biogas through the layer of raw materials, is effective only if the fermented mass has a high rarefaction and does not form crusts on the surface.

Frequency of raw material mixing. Depending on the operating mode of the reactor, mixing can be constant or periodic. A correctly selected mode allows you to significantly reduce the time of fermentation of raw materials and avoid the formation of a crust.

Partial mixing can occur naturally, for example, due to the release of biogas, heat flows or the arrival of fresh raw materials. However, this is not enough to ensure the full efficiency of the process.

Basics of calculation of mechanical mixers. Paddle stirrers usually consist of 2-4 paddles fixed on a rotating shaft (Fig. 3). The blades can be located in the plane of the shaft axis or inclined at an angle of 45° or 60° to the perpendicular plane (Fig. 3, b).

The dimensions of the stirrer blades and the container in which mixing takes place are determined by standard dimensions [12].

$$d = (0,5 ... 0,7)\ D,$$
$$h = (0,08 ... 0,12)\ d, \quad (1)$$
$$b = (0,1 ... 0,5)\ d,$$
$$H = (0,8 ... 1,3)\ D,$$

where d – the blade diameter; D – the diameter of the vessel; b – the height of the stirrer above the bottom; H – the filling height of the device when one agitator is installed; h – the height of the blade.

The peripheral speed at the end of the stirrer blade is selected depending on the viscosity of the mixed mass.

When the height of the vessel exceeds its diameter, as well as when using a viscous liquid, two, three or more pairs of blades are installed on the shaft (in height). The distance between individual pairs of blades is (1...5) d.

For viscous liquids, the walls of the vessel are reinforced with radially arranged bars, over which stirrer blades pass. At the same time, the liquid is captured by the blades, dissected and crushed, which increases the mixing efficiency.

The area of the frontal surface (F_L, m^2) of the mixer blade is determined by the formula:

$$F_L = R \cdot h \cdot \sin\beta, \quad (2)$$

where $R = d/2$ – the pitch of the blade, m; h – height blades, m; β – the angle of inclination of the blade to the direction of movement, deg.

The peripheral speed (ν_0, m/s) of the center of gravity of the blade is equal to:

$$\nu_0 = \frac{\pi X_0 n}{30}, \quad (3)$$

where X_0 – the distance from the center of gravity of the blade to the axis of rotation, m; n – rotation frequency, s^{-1}.

The mass of liquid (q, kg/s) displaced by the blade per unit of time is equal to:

$$q = F_L \cdot v_0 \cdot \gamma, \quad (4)$$

where γ – the volume mass of liquid, kg/m^3.

The blade, having received the specified frequency of rotation and at the same time giving the liquid a speed v_0, performs work A, J:

$$A = \frac{5F_L v_0 \gamma}{g}, \quad (5)$$

where g – the acceleration of free fall, m/s^2.

Blades with the same surface area perform different work, which depends on the R/h ratio. Taking this into account, the work (A, J) based on one blade at a given rotation frequency is expressed by the formula:

$$A = \frac{5\varphi F_L v_0^3 \gamma}{g}, \quad (6)$$

where φ – a coefficient depending on the shape of the blades.

Tabl 1

For rectangular blades φ, depending on the R/h ratio has the following values:

R/h	1	2	4	10	18
φ	1,1	1,15	1,19	1,29	1,4…2,0

In the case of intermediate values of R/h, the coefficient φ is found by straight-line interpolation.

For horizontal rectangular blades, when R = d/2 and $v_0 = (3/4)\cdot v$ the required power (N_h, kW) for the mixer during the start-up period will be:

$$N_h = \frac{2zA_1}{10.2\eta} = \frac{27\varphi 27F_L v^3 \gamma}{642g\cdot 10.2\eta} = 60\cdot 10^{-9}\frac{\varphi z}{\eta}F_L d^3\gamma, \text{kW}, \quad (7)$$

where d – the diameter of the stirrer blade circle, m; υ – the peripheral speed of the tip of the blade, m/s; z – the number of pairs of stirrer blades; η – mechanical efficiency transmission mechanism.

For vertical rectangular blades, the required power (N_V, kW) in the start-up period is determined by the expression:

$$N_V = 18\cdot 10^{-9}\frac{\varphi zh}{\eta}(d_2^4 - d_1^4)n^3\gamma, \text{kW}, \quad (8)$$

where d_2 and d_1 – are the outer and inner diameters of the stirrer, m.

The resistance force of the liquid (P_2, H) acting on the blade of the horizontal stirrer is equal to:

$$P_2 = 10^4\frac{N_V}{\omega d}, \quad (9)$$

where $\omega = \frac{\pi n}{30}$, ω – the angular velocity of the blade, rad/s.

The force P is applied at a distance (x_0, m) equal to:

$$x_0 = \frac{3}{4},\ R = \frac{3}{8}d, \quad (10)$$

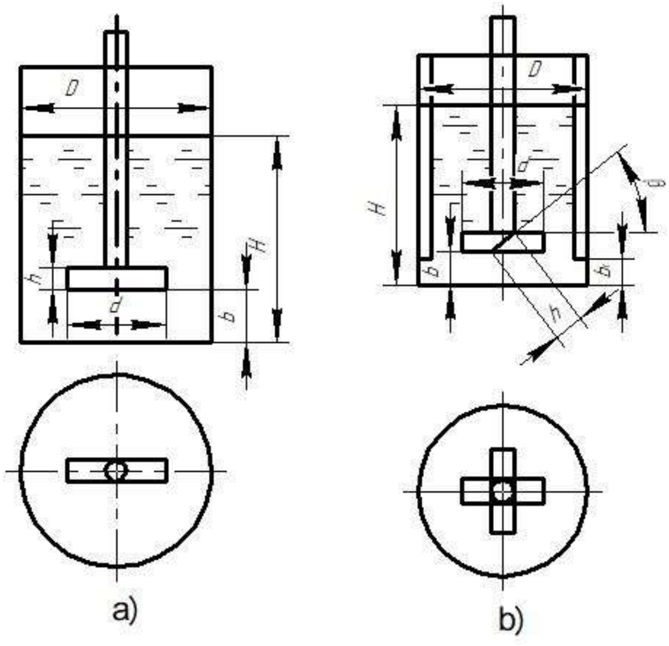

Fig. 3. Shovel stirrers: a – with two blades; b – with four blades

For a vertical blade mixer, the resistance force (P_v, H) of the liquid acting on the blade is determined by the formula:

$$P_V = \frac{10^4 N_V}{\omega d}, \quad (11)$$

This force is applied at a distance, m:

$$x_0 = \frac{3}{8}\frac{d_2^4 - d_1^4}{d_2^3 - d_1^3}. \quad (12)$$

Propeller stirrers are structurally a propeller with the number of blades from two to four, most often with three blades. When rotating, the propeller captures the liquid with its blades and throws it in the opposite direction. The thrown portion hits the liquid in the vessel, spreads in all directions and enters the propeller again.

Thus, intensive circulation of the liquid with a vortex motion is carried out in the vessel, which ensures its active mixing.

Propeller stirrers are successfully used for liquids with a dynamic viscosity of up to 4.0 Pa·s. When the viscosity of the stirred medium is 0.01...1.0 Pa·s, choose a circular speed equal to 4.8...16 m/s. Figure 4 shows a diagram of a mixer with a propeller stirrer 2 located in a diffuser 1.

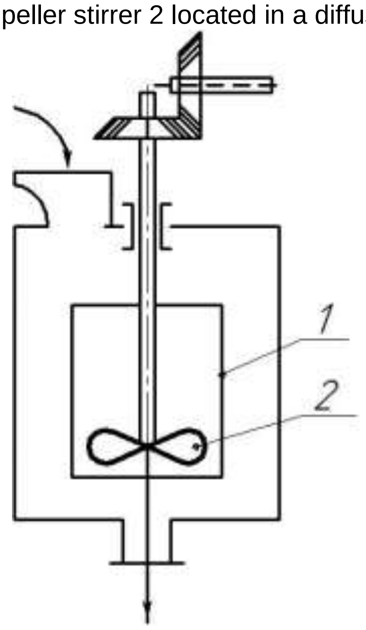

Fig. 4. Mixer with a propeller stirrer: 1 – diffuser; 2 – stirrer

Such mixers are characterized by high pumping action and good circulation of the contents of the vessel during effective mixing. If the fluid flow moves parallel to the axis of the propeller shaft, like a cylinder with a base in the form of a circle described by a screw, then the surface (F, m^2) that is "swept" will be:

$$F = 0{,}8\frac{\pi d^2}{4}, \quad (13)$$

where 0,8 – the jet narrowing coefficient caused by the propeller blades; d – the diameter of the circle described by the extreme point of the blade, m.

There is a relationship between the actual axial velocity υ_0(m/s) of the stirred liquid, the pitch of the screw S and the rotation frequency n:

$$\upsilon_0 = \frac{Sn\cos^2\alpha}{60}, \quad (14)$$

where S – the screw pitch, m; n – the rotation frequency, s^{-1}; α – the angle of rise of the helical line, degrees.

The propeller blade can be imagined as a part of the screw surface, and the liquid can be likened to a nut, which must rise to a height equal to the step S with each revolution of the screw. In fact, the liquid partially slides back, which takes into account the coefficient 0,7...0,8; in calculations, its average value K_{av} = 0,75 is accepted. Therefore, the effective height of the liquid rise per revolution of the screw is equal to:

$$H = K_{av}S = 0{,}75S, \quad (15)$$

The angle α of the rise of the helical line is taken to be equal to 35...45°. The frequency of rotation of the propeller stirrer blades varies within significant limits (6...18 s^{-1}), decreasing with increasing diameter. When mixing viscous liquids containing suspensions, as well as creating foam, the rotation frequency of propeller stirrers is 2,5...8 s^{-1}. The step is not the same for different sections of the blade. However, there are screws with a constant pitch. The step (S, m) is calculated based on the value of the angle of elevation of the helical line and the radius of the blade according to the formula:

$$S = 2nR\mathrm{tg}\alpha = \pi d\mathrm{tg}\alpha, \quad (16)$$

In such devices, the speed of fluid movement caused by the rotation of the screw is determined only by the axial component, that is, the speed of fluid absorption through the screw.

At the multiplicity of liquid mixing (K, min), the axial speed of its absorption (υ_0, m/s) is equal to:

$$\upsilon_0 = \frac{Kq}{60\gamma F_{OM}\gamma} = \frac{KV}{60F_{OM}}, \quad (17)$$

where q and V are, respectively, the mass and volume of the liquid mixed per unit of time, kg/min and m^3/min.

The angular speed of the propeller stirrer blade (ω, rad/s) can be determined by the formula:

$$\omega = \frac{2n\upsilon_0}{S\cos^2\alpha} = \frac{2\upsilon_0}{d\mathrm{tg}\alpha\cdot\cos^2\alpha} = \frac{2\upsilon_0}{d\sin\alpha\cdot\cos\alpha}, \quad (18)$$

The required power (N_n, kW) of the propeller mixer drive is determined by the expression:

$$N_n = \frac{K_{av}\gamma F_{OM}}{10{,}2\eta} S\cdot n\cdot\cos\alpha. \quad (19)$$

Usually, the following ratios of propeller mixer parameters are accepted [3]: mixer diameter d = (0,25...0,33) D; screw pitch S = (1...3) d; the height of the blade above the bottom h = (0,5...1,0) d; the filling height of the device when installing one stirrer blade H = (0,8...1,2) D and several stirrer blades H = (1,0...5,0) D; immersion depth of the stirrer (H – h) = (2,0...4,0) d; distance between two propellers on the shaft (1,0...5,0) d; rotation frequency n = 7...40 s^{-1}.

Planetary stirrers are used for very thick liquids with a dynamic viscosity of up to $200Pa\cdot s(\frac{kgF\cdot s}{m^2})$. The functional diagram of a planetary stirrer is shown in figure 5. When shaft 4 rotates, carrier 2 captures the stirrer shaft 6 and the blades mounted on it 7. The latter carry out a complex movement, rotating around the axis of the shaft 6 and together with it around the carrier. Each point of the blade describes a complex curve. The speed of the point is tangential to the trajectory of its movement and continuously changes in direction and magnitude, due to which intense turbulent fluid movement occurs in planetary mixers.

Paddle mixers are universal continuous machines designed for efficient mixing of various materials in industries such as construction, chemical processing, food production, and metallurgy. These mixers ensure homogeneous blending of dry, moist, or semi-liquid components, making them suitable for applications requiring consistent quality and high throughput.

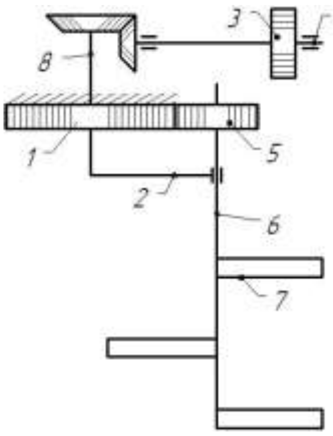

Fig. 5. Planetary mixer: 1, 3, 5 – gears; 2 – carrier; 4 – shaft; 6 – agitator shaft; 7 – blades; 8 – drive shaft

Paddle and screw batch mixers are designed to handle a variety of materials, including dry powders, moist feeds, and slurry-like substances. Their load capacities are typically characterized by the filling coefficient (Kz), which indicates the proportion of the mixer's total volume that can be effectively utilized during operation:

- paddle batch mixers can be loaded with wet feeds up to K_z = 0.8, meaning they can utilize up to 80% of their total capacity. This is due to their efficient paddle arrangement, which ensures proper material movement and prevents excessive buildup or clogging.
- screw batch mixers, on the other hand, have a slightly lower maximum load capacity of K_z = 0.7, meaning they can be filled up to 70% of their total volume. This is because screw mixers rely on the movement of an internal helical blade, which requires sufficient space to effectively transport and mix materials without excessive resistance or material accumulation.

The productivity of a continuous horizontal paddle mixer (q, kg/s) is determined by the formula:

$$q = \frac{D^2 S\omega\gamma K_z}{8}, \quad (20)$$

where D – the outer diameter of the blade, m; S – the pitch of the blades, m; ω – the angular velocity, rad/s; γ – the volumetric mass of the feed, kg/m³; K_z – the capacity filling coefficient (K_z=0.3).

It is essential to consider the extreme flexibility of the shovels emerging from the ground to ensure that the sub-central force $m\omega^2 R_L$ (where R_L represents the maximum radius of the shovel's curvature, meters) does not cause the displacement of all particle masses. Otherwise, the particles may detach from the shovel and settle outside the active mixing process. The condition $m\omega^2 R_L \leq mg$ determines the critical (maximum permissible) angular velocity of the mixer blades:

$$\omega_{cr} = \sqrt{\frac{g}{R_L}}, \quad (21)$$

The required power to drive the paddle mixer is determined taking into account the resistances acting on the paddle. Let us consider the diagram of the forces (Fig. 6) acting in the plane perpendicular to the axis of the mixer shaft when the paddle is immersed in the mixed feed. The resultant R of all resistances deviates from the normal N by an angle φ of friction.

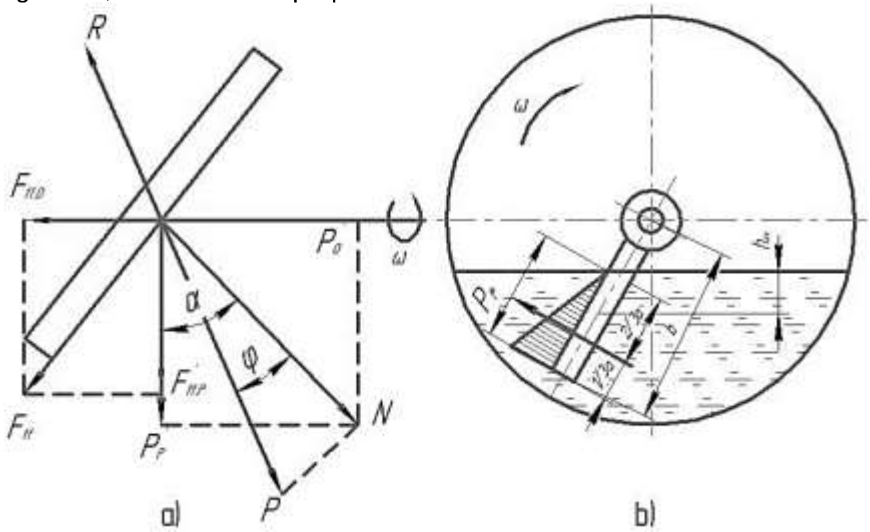

Fig. 6. Scheme of forces acting on the blade (A) and calculation scheme (B) of the blade mixer: a –the length of the part of the blade immersed in the feed; b – is the total length of the blade

To overcome this force, it is necessary to apply an equal to it, but oppositely directed force P from the side of the blades. We will decompose the normal component P_n of this force along the directions of the circumferential and axial velocities, as a result we will obtain the force P_p, which gives the particles rotational motion, and the force P_0, moving these particles in the axial direction. At the same time, $P'p = P_n\cos\alpha$ and $P'_0=Pn\sin\alpha$ (here α is the angle of inclination of the blade to the axis of rotation of the mixer shaft, degrees).

In addition, under the action of the normal component of the force R in the plane of motion of the particles along the blade, a friction force $F_{ff} = fP_n$ occurs, directed against the relative motion of the particles along the blade. Let's decompose the friction force F_{ff} into surrounding and axial components:

$$\acute{F}_{ff.p} = F_{ff}\sin a = fP_n sina, \quad (22)$$

$$\acute{F}_{ff.0} = F_{ff}\cos a = fP_n cosa. \quad (23)$$

Summing up the received vectors in the directions, we get the value of the circumferential force:

$$P_p = \acute{P}_p + \acute{F}_{ff.p} = P_n(cosa + f sina) \quad (24)$$

and axial force:

$$P_0 = \acute{P}_0 - \acute{F}_{ff.0} = P_n(sina - f cosa). \quad (25)$$

When moving a blade immersed in the material, supports are distributed along it according to the law of a triangle (Fig. 6, b) and the point of application of the net force R is located in the center of gravity of this triangle, i.e. at a distance r_{av}, equal to 2/3 of the length of the blade from the axis of rotation. When the capacity is not filled to the norm and the blade is rotating, the immersion depth of the latter is a variable value. In this case, the normal component of P_n, resistance forces is determined by the formula:

$$P_n = 9.81\gamma h_{av} F_L t_g^2\left(45 + \frac{\varphi}{2}\right), \quad (26)$$

where h_{av} – the average depth, equal to half of the greatest immersion depth of the blade, m; F_L – the projection of the area of the blade immersed in the material onto the directed rotations, m^2; φ – the angle of internal friction, deg.

The angled blades of the mixer act like a screw and transmit the circumferential (rotational) V_p and axial V_0 velocities to the mixed mass.

Circular speed: $V_p=\omega r_{av}$ (here r_{av} is the average radius, or the distance from the axis of rotation to the point of application of the equivalent resistance forces).

Axial velocity: $V_0 = V_p cos\alpha sin\alpha$ (here α – angle of inclination of the blade to the axis of rotation of the mixer shaft, degrees).

The required blade drive power (N_L, kW) of the mixer is determined by the expression:

$$N_L = \frac{1}{100}(P_P V_P + P_0 V_0)Z_L, \quad (27)$$

where Z_L – the number of simultaneously dipping blades.

Conclusions. To ensure efficient operation of the reactor, mixing of raw materials must be carried out regularly. Insufficient mixing frequency leads to the formation of stagnation zones, delamination of the raw material mass and the formation of a crust on its surface. This, in turn, significantly reduces the efficiency of the gas formation process, as the contact area between the substrate and the methane bacteria decreases. High-quality and timely mixing allows you to increase the yield of biogas up to 50%, ensuring an even distribution of temperature, nutrients and microorganisms in the reactor.

Excessively frequent stirring can have a negative effect on the fermentation process, causing a violation of the stability of the microbiological environment inside the reactor. This can lead to a decrease in the efficiency of decomposition of organic matter and, as a result, the discharge of partially processed raw materials. The best option is careful but intensive stirring at intervals of 4-6 hours. This mode allows you to maintain a balance between the stability of the process and the required intensity of mixing.

For effective biogas extraction, it is important to take into account the type of raw material, its physical and chemical properties, as well as the volume of the reactor. The choice of agitator type (blade, screw, pneumatic, etc.) should be based on these characteristics and the technical capabilities of the system. In addition, it is necessary to carry out a detailed calculation of the main geometric and power parameters of the mixer, such as length, width, angle of inclination of the blades, as well as the speed of rotation of the shaft. Correct selection and calculation ensure maximum mixing efficiency, prevent the formation of stagnation zones and crusts, and also contribute to optimal biogas extraction with minimal energy costs.

References

1. Tokarchuk D. M., Pryshliak N. V., Tokarchuk O. A., Mazur K. V. (2020). Technical and Economic Aspects of Biogas Production at A Small Agricultural Enterprise With Modeling Of The Optimal Distribution Of Energy Resources For Profits Maximization. *INMATEH – Agricultural Engineering*. № 61 (2). P. 339–349. https://doi.org/10.35633/inmateh-61-36 [in English].

2. Kupchuk I., Burlaka S., Galushchak A., Yemchyk T., Galushchak D., Prysiazhniuk Y. (2022). Research of autonomous generator indicators with the dynamically changing component of a two-fuel mixture. *Polityka*

Energetyczna. Vol. 25, Issue 2. P. 147-162. https://doi.org/10.33223/epj/150746 [in English].

3. Furman I.V., Ksenchyn D.O. (2024). Upravlinnia vyrobnytstvom biohazu z vidkhodiv pidpryiemstv APK ta domohospodarstv [Management of biogas production from waste of agricultural enterprises and households]. *Ekonomika ta suspilstvo*. № 59. URL: https://economyandsociety.in.ua/index.php/journal/article/view/3398/3325 https://doi.org/10.32782/2524-0072/2024-59-44 [in Ukrainain].

4. Honcharuk I., Tokarchuk D., Gontaruk Y., Kolomiiets T. (2024). Production and Use of Biogas and Biomethane from Waste for Climate Neutrality and Development of Green Economy. *Journal of Ecological Engineering*. Vol. 25. Issue 2. P. 20-32. https://doi.org/10.12911/22998993/175876 [in English].

5. Kaletnik H.M., Honcharuk I.V. (2020). Ekonomichni rozrakhunky potentsialu vyrobnytstva vidnovliuvalnoi bioenerhii u formuvanni enerhetychnoi nezalezhnosti ahropromyslovoho kompleksu [Economic calculations of the potential of renewable bioenergy production in the formation of energy independence of the agro-industrial complex]. *Economy of AIC.* № 9. P. 6-16. https://doi.org/10.32317/2221-1055.202009006

6. EBA Statistical Report 2024. *europeanbiogas.eu* URL: https://www.europeanbiogas.eu/eba-statistical-report-2024 [in English].

7. Ukrainian Bioenergy Association (2020). Perspektyvy vyrobnytstva biometanu v APK Ukrainy [Prospects for biomethane production in the agro-industrial complex of Ukraine]. *uabio.org.* URL: https://uabio.org/wp-content/uploads/2020/09/Dombrovskyi_MHP_29092020.pdf [in Ukrainain].

8. Pryshliak N.V., Tokarchuk D.M., Palamarenko Ya.V. (2020). Rekomendatsii z vyboru optymalnoi syrovyny dlia vyrobnytstva biohazu na osnovi eksperymentalnykh danykh shchodo enerhetychnoi tsinnosti vidkhodiv [Recommendations for choosing the optimal raw material for biogas production based on experimental data on the energy value of waste]. *Investments: practice and experience*. № 24. P. 58–66. 10.32702/2306-6814.2020.24.58 [in Ukrainain].

9. Hontaruk Ya.V. (2024). Upravlinnia resursnym zabezpechenniam proektiv z vyrobnytstva biohazu ta dyhestatu [Resource management of biogas and digestate production projects]. *Economy and society.* № 62. URL: https://economyandsociety.in.ua/index.php/journal/article/view/4055/3985 https://doi.org/10.32782/2524-0072/2024-62-173 [in Ukrainain].

10. Paziuk V. M., Tokarchuk O. A. (2022). Osnovni kharakterystyky osadiv stichnykh vod [Main characteristics of sewage sludge]. *Engineering, Energy, Transport AIC.* №1 (116). P. 96–104. DOI: http://doi.org/10.37128/2520-6168-2022-1-11 [in Ukrainain].

11. Lohosha, R., Palamarchuk, V., Krychkovskyi V. (2023). Economic efficiency of using digestate from biogas plants in Ukraine when growing agricultural crops as a way of achieving the goals of the European Green Deal. *Polityka Energetyczna.* Vol. 26, Issue 2. P. 161–182. https://doi.org/10.33223/epj/163434 [in English].

12. Omelianov O. M., Tokarchuk O. A. (2022). Obgruntuvannia amplitudno-chastotnykh kharakterystyk ta konstruktyvnykh parametriv separatora z vibratsiinym pryvodom zbudzhennia prostorovykh kolyvan [Substantiation of amplitude-frequency characteristics and design parameters of a separator with a vibration drive for excitation of spatial vibrations]. *Vibrations in engineering and technologies*. № 1 (104). P. 30–37. https://doi.org/10.37128/2520-6168-2022-1-4 [in Ukrainain].

ІННОВАЦІЙНІ ПІДХОДИ ВИКОРИСТАННЯ ПРОДУКТІВ БІОГАЗОВИХ ТЕХНОЛОГІЙ

В умовах Вінницької області, яка має сприятливі умови для сільського господарства та переробної промисловості, актуальною проблемою залишається утилізація органічних відходів тваринництва, зокрема птахівництва. Традиційні технології переробки не забезпечують ефективного знезараження та дезодорації відходів, що обмежує можливості їх використання як добрив. Впровадження енергозберігаючих систем утилізації та знезараження відходів дозволяє суттєво підвищити економічну ефективність агропромислових підприємств і зменшити екологічні ризики.

Особливу увагу приділено біоконверсії органічних речовин шляхом анаеробного зброджування, що дозволяє отримувати біогаз із високою економічною ефективністю. Метанове зброджування характеризується різноманітним видовим складом мікрофлори, що сприяє адаптації процесу до змін сировини. Водночас в умовах України необхідне використання високотехнологічних підходів для оптимізації біогазових установок, враховуючи кліматичні та економічні особливості.

У роботі проаналізовано методи підвищення ефективності роботи БГУ. Зокрема, запропоновано вдосконалення

систем термостабілізації, перемішування субстрату та утилізації теплоти збродженого матеріалу. Розглянуто основні технологічні аспекти перемішування субстрату, що є критичним фактором стабільної роботи реактора. Ефективне переміш ування забезпечує: запобігання утворенню кірки та осаду, які знижують об'єм активної зони реактора. Рівномірний розподіл температури та популяції бактерій у реакторі. Інтенсифікацію виділення біогазу з товщі субстрату.

На основі проведених досліджень зроблено висновок, що регулярне перемішування кожні 4-6 годин дозволяє підвищити вихід біогазу на 50%, тоді як надмірно часте перемішування може негативно вплинути на ферментацію. Рекомендовано адаптувати частоту перемішування та вибір типу мішалки до специфічних умов експлуатації реактора.

Отримані результати можуть бути використані для проектування та модернізації біогазових установок, що сприятиме підвищенню енергоефективності агропромислових підприємств та розвитку альтернативної енергетики.

Ключові слова: *біогазові установки, перемішування субстрату, метанове зброджування, енергоефективність, альтернативна енергетика, утилізація відходів, вихід біогазу.*

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