Determination of the Energy Efficient Speed of the Working Body of the Agitator for Small Biogas Reactors

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Abstract. The aim of the work is to determine the energy-efficient speed level of a two-tier paddle mixer with blades installed at an angle of 90° to improve the energy efficiency of the biogas formation process in small biogas reactors. To achieve the set goals, physical methods, three-dimensional modeling, processing and visualization of results in application programs were used. The working hypothesis of the research is that 3D modeling will allow determining the nature of the distribution of biomass flows and the amount of energy expended depending on the rotation speed of the mixing device. The most important result of the study is the obtaining of graphical dependencies of the trajectories of movement of elementary volumes and the velocities of substrate flows at different rotation speeds of the stirrer. The significance of the research results is that, based on the flows of raw materials in the reactor, it was established that for a reactor with the geometric parameters specified in the work, the energy-efficient rotation frequency of the paddle mixer with blades at an angle of 90° is within 40…50 rpm. The average speed of the substance is in the range of 0.273 – 0.348 m/s. It was found that the dependence of the consumed energy on the mixer rotation speed corresponds to a power function. The percentage of useful energy spent in starting and operating modes for different rotation speeds was determined. The obtained data can be used for upgrading and designing mixing systems in small biogas reactors.
***Keywords*:** energy consumption, small biogas reactors, energy efficiency, modeling, mixing, rotation speed, flow vectors.

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Determinarea vitezei eficiente energetice a corpului de lucru al agitatorului pentru reactoare mici cu biogaz

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Rezumat. Scopul lucrării este de a determina nivelul de viteză eficient din punct de vedere energetic al unui mixer cu palete cu două niveluri cu palete instalate la un unghi de 90° pentru a îmbunătăți eficiența energetică a procesului de formare a biogazului în reactoarele de biogaz mici. Pentru atingerea obiectivelor stabilite s-au folosit metode fizice, modelare tridimensională, prelucrare și vizualizare a rezultatelor în programe de aplicație. Ipoteza de lucru a cercetării este că modelarea 3D va permite determinarea naturii distribuției fluxurilor de biomasă și a cantității de energie cheltuită în funcție de viteza de rotație a dispozitivului de amestecare. Cel mai important rezultat al studiului este obținerea dependențelor grafice ale traiectoriilor de mişcare a volumelor elementare și a vitezelor de curgere a substratului la diferite viteze de rotație ale agitatorului. Semnificația rezultatelor cercetării este că, pe baza fluxurilor de materii prime din reactor, s-a stabilit că pentru un reactor cu parametrii geometrici specificați în lucrare, frecvența de rotație eficientă energetic a malaxorului cu palete la un unghi de 90° este cuprinsă între 40…50 rpm. Viteza medie a substanței este în intervalul 0.273 – 0.348 m/s. S-a constatat că dependența energiei consumate de viteza de rotație a mixerului corespunde unei funcții de putere. A fost determinat procentul de energie utilă cheltuită în modurile de pornire și de funcționare pentru diferite viteze de rotație. Datele obținute pot fi utilizate pentru modernizarea și proiectarea sistemelor de amestecare în reactoare de biogaz mici.
Cuvinte-cheie: consum de energie, reactoare mici de biogaz, eficiență energetică, modelare, amestecare, viteză de rotație, vectori de flux.

Определение энергоэффективной частоты вращения рабочего органа мешалки для малых биогазовых реакторов

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Аннотация. Целью работы является определение энергоэффективного уровня скорости перемешивающего элемента электромеханической системы в виде лопастного двухъярусного смесителя с лопастями, установленными под углом 90°, для повышения энергетической эффективности процесса образования биогаза в малых биогазовых реакторах и рентабельности его дальнейшей переработки. Для достижения поставленных целей использовались общие методы физики, трехмерное моделирование, обработка и визуализация результатов в программах SolidWorks Flow Simulation, Wolfram Mathematica. Рабочая гипотеза исследований заключаеться в том, что выполнение 3D моделирования позволит определять характер распределения потоков биомассы в зависимости от скорости вращения лопастного перемешивающего устройства, что в свою очередь позволяет определить количество затраченой энергии на процес перемешивания. Найболее важный результат исследования заключается в получении зависимостей траектории движения элементарных объемов и скорости потока субстрата при различных скоростях вращения мешалки, а также получении графических зависимостей изменения средней скорости субстрата в объеме биогазового реактора за первые 20 секунд работы. Значимость приведенных в работе результатов исследования заключается в том, что на основе потоков сырья в реакторе установлено, что для реактора с геометрическими параметрами задаными в работе, энергоэффективная частота вращения смесителя лопастного типа с лопастями под углом 90° находится в пределах 40…50 об/мин. Средняя скорость движения вещества находиться в диапазоне 0.273 – 0.348 м/с. Определено процентное значение количества полезной энергии, необходимой для пускового периода, от полезной энергии, потребляемой за период перемешивания при различных скоростях вращения. Установлено, что зависимость потребляемой энергии от увеличения частоты вращения рабочего органа смесителя соответствует степенной функции. Приведенные в работе данные могут использоваться при проектировании и модернизации систем перемешивания субстрата в малых биогазовых реакторах.

Ключевые слова: расход энергии, малые биогазовые реактори, энергоэффективность, моделирование, смешивание, скорость вращения, векторы потока.

INTRODUCTION

In recent years, the issue of energy supply of countries is very relevant. As evidenced by a significant number of studies and raising the issue of introducing alternative energy sources into the existing energy system of countries around the world [1-3]. One of the pressing issues is gas supply to the population and production facilities. An alternative method of gas production is biogas technologies, which allow the use of specially designed tanks – fermentation vats, and the processing of waste from distilleries [4, 5], large and small livestock and agricultural complexes into biogas. The research used a biogas plant in the form of a 30-liter cylindrical tank [4-7].

Studies [6-9] present the results of studies confirming the rationality of using biogas generated from animal and crop waste for heating premises and refueling cars.

From an ecological point of view, it is relevant to introduce various systems for the utilization and use of accumulated waste [10, 11]. Taking into account the experience of European countries [12, 13] in the field of renewable energy use, as well as information provided at summits [14-16] regarding the potential of countries to implement biogas technologies [17], it can be argued that an urgent issue is to increase their number.

There is an intensive spread of small-scale home biogas plants in different countries of the world, in which household food waste is fermented [18]. The use of small biogas plants allows you to perform several important tasks at once, namely: the disposal of food waste with the subsequent production of biogas and its use for your own needs for heating, cooking and other household chores; the disposal of waste in biogas reactors allows you to obtain environmentally friendly fertilizers for use in your own needs on homestead plots or for sale to farming companies.

The main problem in biogas production is the need to control and optimize operating conditions, namely: temperature, acidity and humidity levels, nutrient ratios at all stages of fermentation, maintaining the suspended state of the substrate through mixing. In accordance with the above, the cost of biogas produced depends on the costs of creating the necessary conditions for fermentation.

The most energy-intensive process in biogas production is maintaining the fermentation temperature [19-21] within the established permissible limits. Another energy-intensive process is mixing, the main need of which is aimed at avoiding the appearance of sediment and compaction of the fermented substance.

The high cost of maintaining the necessary parameters of raw material fermentation reduces the demand and interest of producers in implementing and investing in biogas technologies.

To address the current issue, to increase the attraction of additional investment in biogas technologies for the purpose of more intensive implementation of alternative energy sources in the country's energy system, states are introducing programs aimed at encouraging the use of alternative energy [22-24].

The work [25] present the results of scientific research aimed at increasing the productivity of biogas production and reducing the cost of the generated volume of biogas.

Special attention of scientists is focused on the field of research related to reducing energy costs for mixing [26, 27], as well as heating organic matter with various types and designs of heaters [28, 29].

Today, biogas reactors use a large number of methods and technical means for mixing, including hydraulic, submersible electric motors [27, 30], and electromechanical converters of various designs. However, one of the promising equipment for intensification of biomass fermentation is biogas reactors with mechanical mixers [31, 32].

In work [33] the results of scientific research on the effectiveness of careful mechanical mixing of biomass are presented, since the careful mixing regime ensures the preservation of the integrity of bacterial colonies. After all, it is the bacteria that play the main role in methane formation and biogas quality.

In work [34] it is proved that the power consumption of the mixer is significantly influenced by its geometric parameters, its operating mode and the frequency of rotation of its working body.

In work [35] the results of scientific research are presented, which confirm the effectiveness of combining electric heating and mixing into one thermomechanical system. Our previously published works from 2021-2023 present the results of theoretical studies of the thermomechanical system, which are confirmed by comparative analysis with experimental studies.

The authors [36] describe the process of studying the rotation frequency of a six-bladed mixer on the distribution of flow vectors in a tank using CFD modeling. It was established that the most important parameter affecting the optimal distribution of vectors is the rotation speed of the mixer working body.

The authors [37] present multiphase approaches to CFD modeling, turbulence models and bacterial population balance models. The need to control the mixing speed and shear stress of the substrate masses in transient modes is indicated to avoid the destruction of living organisms under the influence of the mechanical action of the mixing device.

The work [38] provides an analysis of the hydrodynamic shear stresses generated by various combinations of impellers in a stirred bioreactor. Also, the work found that a decrease in shear stress leads to an increase in the growth of microorganisms in the substance. All this indicates the relevance of research aimed at finding a rational frequency of mixing substances in cylindrical reactors.

In [39], the results of theoretical studies of the influence of rotation speed on the initial energy pulse transmitted to the substance during mixing are presented. However, according to the study, the mixer blade is replaced by a source of energy pulse transmitted to the substance. This method makes it easier to generate the configuration of the tank and the computational grid, but does not take into account the mass-dimensional features of the blades.

At the 2023 UN Climate Change Conference (COP-28), held in Dubai, a collective decision was made to increase the share of alternative energy in countries' energy systems by 2050. A prerequisite for this is a prior increase in renewable sources and an increase in their energy efficiency by 2030. Taking into account the above, as well as the information presented at (COP-28), a relevant issue is research into increasing the energy efficiency of biogas technologies in order to spread alternative energy and introduce it into the energy system.

Analysis of research by scientists from different countries of the world indicates that mixing of organic biomass is an energy-intensive process. Therefore, the issue of establishing an energy-efficient rotation rate of the working body of the mixing device to reduce energy costs for mixing still remains relevant. As a result, this will increase the profitability of biogas production and interest potential investors.

The aim of the work is to determine the energy-efficient speed level of the mixing element of the electromechanical system in the form of a bladed double-deck mixer with blades installed at an angle of 90° for small biogas reactors.

RESEARCH METHODOLOGY

Considering the above positive factors from the use of small biogas plants and the relevance of the issue of reducing energy consumption for the mixing process, in order to determine the energy-efficient rotation frequency of the mixing device, the following steps were performed:

1) a mathematical model was built to determine the operating and starting power of the mixing device;
2) 3D modeling was performed to determine the distribution vectors of biomass flows depending on the rotation speed of a bladed double-deck mixer with blades installed at an angle 90°;
3) the influence of the mixer rotation frequency on the distribution pattern of biomass flows in the biogas reactor was investigated;
4) graphs of the useful power of the mixing device at the beginning of mixing at different rotation speeds were obtained and investigated;
5) the amount of energy spent on mixing biomass during the start-up period and the entire mixing period for different rotation speeds was determined.

During the working period, the power of the mixing device is largely determined by the resistance created by the liquid on the area of the mixing blade. The resistance created by the medium to the body moving in it is determined by Newton's law:

$$S = \zeta \cdot F \cdot \frac{\omega^2 \cdot \gamma}{2 \cdot g}, \quad (1)$$

where ζ – drag coefficient, which depends on the mode of movement of the medium; ω – speed of movement of the blade in the medium, m/s; γ – specific gravity of the medium, kgf/m^3; g – acceleration of gravity, m/s^2; F – area of projection of the blade onto a plane perpendicular to the direction of movement, m^2;

$$dF = dx \cdot h, \quad (2)$$

where dx – the blade element is placed at a distance x from the axis of rotation, m; h – the height of the blade projection onto the mixed medium, m.

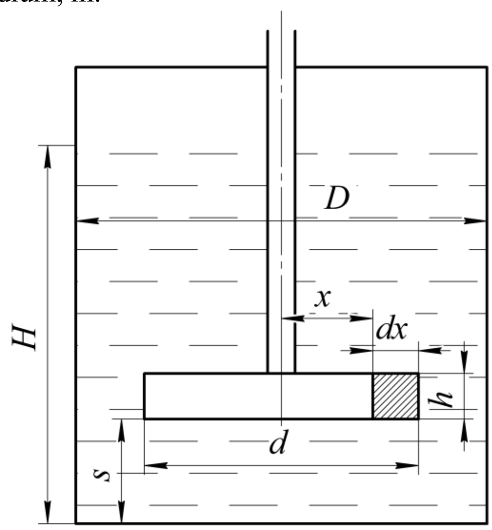


Fig. 1. Scheme of a blade mixer.

Considering a certain blade element (Fig. 1) located at a distance x from the axis of rotation, we can determine the working power (dP_p) required to overcome the resistance of the medium to the moving blade:

$$dP_p = dS \cdot \omega, \quad (3)$$

where dS, for two blades:

$$dS = 2 \cdot \zeta \cdot dF \cdot \frac{\omega^2 \cdot \gamma}{2 \cdot g}, \quad (4)$$

$$\omega = 2 \cdot \pi \cdot n \cdot x, \quad (5)$$

where n – blade rotation frequency, rpm; x – distance from the axis of rotation to the blade element dx, m.

Substituting dependence (2, 4 and 5) into dependence (3), we obtain the following dependence:

$$dP_p = \frac{(2\pi)^3 \cdot \gamma \cdot \zeta \cdot n^3 \cdot h \cdot x^3 \cdot dx}{g}, \quad (6)$$

By integrating dependence (6) within the limits of $x=0...r$, and replacing the specific gravity (γ) with the density of the substance (ρ), we obtain:

$$P_p = k \cdot \zeta \cdot d^5 \cdot n^3 \cdot \rho \quad (7)$$

where,

$$k = 3.87 \cdot a \quad (8)$$

where a – this is the ratio of the blade height to its diameter.

From dependence (7) we get:

$$k \cdot \zeta = \frac{P_p}{\rho \cdot d^5 \cdot n^3} \quad (9)$$

Thus, the dependence (9) is a definition of the Euler hydrodynamic similarity criterion (Eu_m), which depends on the Reynolds criterion.

In previously published works, experimental data on the dependence of the Euler criterion on the Reynolds criterion are presented in the form of curves $Eu_м = f(\mathrm{Re}_м)$.

Accordingly, taking into account the Reynolds and Euler criteria, the working capacity of the mixer is described by the dependence:

$$P_p = Eu_м \cdot n^3 \cdot d^5 \cdot \rho, \quad (10)$$

During the working period, the power of the mechanical mixer is spent on overcoming friction forces, that is, on overcoming the resistance created by the substance on the area of the moving blade.

At the initial moment of the blade mixer movement, the power is spent on overcoming the inertia forces (P_i) and friction forces (P_m=P_p) of the medium in order to disturb it:

$$P_n = P_i + P_p, \quad (11)$$

The determination of the power required to overcome the inertial forces of the substance depends on the blade area (*dF*), which during the movement time (1 s) removes a certain volume of substance (*dV*) from the rest state:

$$dV = dF \cdot \omega, \quad (12)$$

where ω – speed of movement of the blade, (dependence 5).

Mass of substance lifted by the blade (d_m):

$$dm = \frac{dF \cdot \omega \cdot \gamma}{g}, \quad (13)$$

where γ – specific gravity of the substance, kgf/m^3.

The power spent on disturbing the mass of matter lifted by the blade, taking into account the value of the velocity (5) and mass (13):

$$dP_i = \frac{(2\pi)^3 \cdot \gamma \cdot n^3 \cdot h \cdot x^3 \cdot dx}{2g}, \quad (14)$$

By integrating dependence (14) within the range *x=0...r*, and replacing the specific gravity (γ) with the density of the substance (ρ), as well as taking into account the Reynolds and Euler criteria, we obtain the equation for calculating the starting power of the mixer:

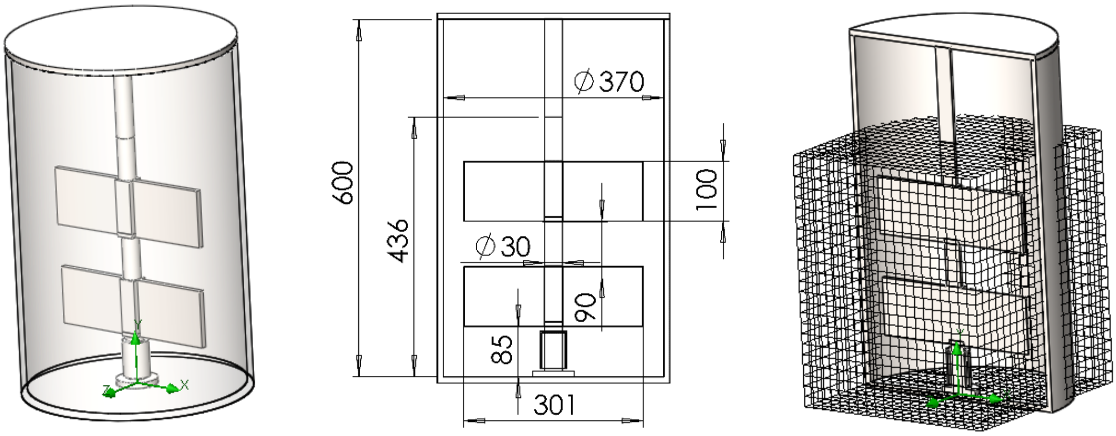
$$P_n = (k + Eu_м) \cdot d^5 \cdot n^3 \cdot \rho \quad (15)$$

The initial moments of movement of mixing devices are accompanied by large energy costs, which depend on the speed of rotation of the mixer. Further mixing of substances in closed volumes is accompanied by the appearance of counterflows, which arise as a result of the reflection of the liquid from the walls of the reactor and affect the increase in energy costs for mixing. Accordingly, the more energy is transferred to the flow from the mixing blade, the greater the speed of the reverse flow. Therefore, to determine the «rational» frequency of rotation of the working body of the mixing device, 3D modeling was performed to determine the distribution vectors of biomass flows depending on the speed of rotation of the bladed double-deck mixer with blades installed at an angle of 90^0. The works [36-39] indicate that the study based on computational fluid dynamics (CFD) can be effectively used for the analysis, design and scaling of mixing systems and biogas reactors.

The SolidWorks software package was used to create a model of a cylindrical biogas reactor with a volume of 60 liters with a bladed double-deck mixer with blades installed at an angle of 90°. The mixing process was simulated using the SolidWorks Flow Simulation application, using the Navier-Stokes equations.

To conduct 3D modeling in the SolidWorks Flow Simulation program, the following physicochemical parameters of organic biomass loaded into the biogas reactor were specified:

density $\rho = 1024$ kg/m^3; dynamic viscosity coefficient $\mu = 0.048$ Pa·s.



a) b) c)

Fig. 2. Biogas reactor model: a) model of a biogas reactor with a paddle double-deck mixer with blades installed at an angle of 90°; b) geometric dimensions of the biogas reactor and a paddle double-deck mixer with blades installed at an angle of 90°; c) computational grid of the geometric model of the biogas reactor.

In Figure 2 a, a model of a biogas reactor of cylindrical shape with a bladed double-tier mixer with blades installed at an angle of 90° placed along the central axis of the reactor is presented. Overall dimensions Figure 2 b and the calculation grid of the biogas reactor Figure 2 c, the upper level of which coincides with the substrate level in the reactor $H = 0.436$ m. For the study, the rotation speed of the paddle double-deck mixer with blades set at an angle of 90° was set within the limits $n = 10...60$ rpm.

RESULTS AND DISCUSSION

As a result of 3D modeling at different speeds of rotation of the bladed double-deck mixer, pictures of the trajectories of movement of elementary volumes and substrate flow velocities in three-dimensional space were obtained Figure 3. As well as graphical dependences of changes in the average substrate velocity in the volume of the biogas reactor Figure 4.

From (Figure 3, a and b) it is noticeable that the trajectories of movement of elementary volumes are concentrated in the central part of the tank with a pronounced accumulation of flows in its upper and central parts. The average velocity of substrate flows in the tank volume is 0.051 m/s (Figure 3, a) and 0.1 m/s (Figure 3, b). At the same time, quiet zones are observed near the walls and at the bottom of the tank, which indicates insufficient mixing of the substance in the small-volume biogas reactor at a rotation frequency of the mixer working element of 10 rpm and 20 rpm.

When a mechanical two-tier mixer rotates, the tiers of which are placed in parallel, and the blades are installed at an angle of 90° at a speed of 30 rpm (Figure 3, c), the flow movements acquire maximum speeds near the blades of the mixing device. However, it should be noted that in the upper layers of the substance and between the tiers of the blades, the speed of elementary volumes acquires values from 0 to 0.260 m/s. While, the average speed of movement of elementary volumes of the substance is 0.2 m/s (Figure 4, a).

Based on the analysis of the graphical dependencies presented in Figure 3, a, b and c, it was concluded that for the design of the mixing device shown in Figure 2, the rotation speed, which does not exceed 30 rpm, does not allow for effective mixing of the substance in a small-volume biogas reactor for a short time.

At a mixing device rotation frequency of 40 rpm (Figure 3, d), the movement of elementary volumes acquires maximum velocities near the edges of the mixer blades. In the upper layers of the substance, an accumulation of flows and an increase in velocities are observed, which is caused by the formation of a funnel. In the upper layers and between the tiers of blades, the flow velocity during the mixing process is in the range from 0.1 to 0.417 m/s. In the lower part of the tank, areas of substance lifting from the bottom of the tank are observed, which arise due to centrifugal forces during the rotation of the mixer blades and the appearance of a suction effect. It is known that compaction of the sediment leads to a decrease in nutrients for bacteria and, as a result, a decrease in the formation of biogas volume and decomposition of organic matter. Therefore, the rise of matter from the bottom of the tank plays one of the main roles in the process of anaerobic fermentation. The average speed of movement of elementary volumes of matter is 0.273 m/s (Figure 4, b).

At a rotation speed of 50 rpm (Figure 3, e), a flow movement pattern similar to the one shown in (Figure 3, d) is observed. The difference is the flow velocity, the values of which are: in the upper part of the tank from 0.1 to 0.5 m/s; in the area between the blade tiers from 0.083 to 0.4 m/s and in the lower part of the tank from 0.1 to 0.3 m/s, while the average velocity of movement of elementary volumes of matter in the tank is 0.348 m/s (Figure 4, c).

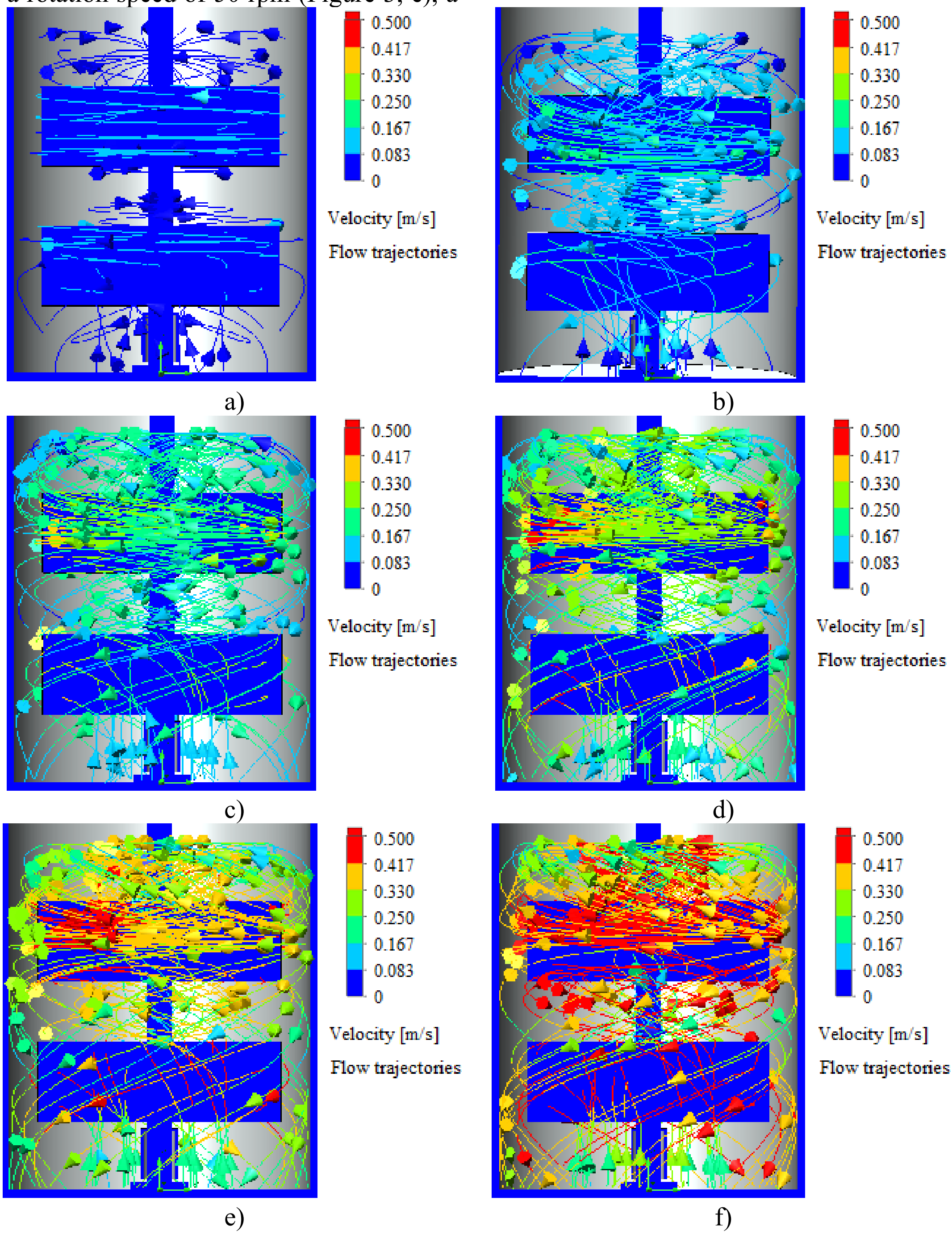


Fig. 3. Trajectories of movement of elementary volumes and substrate flow velocities at different mixer rotation speeds: a) 10 rpm; b) 20 rpm; c) 30 rpm; d) 40 rpm; e) 50 rpm; f) 60 rpm.

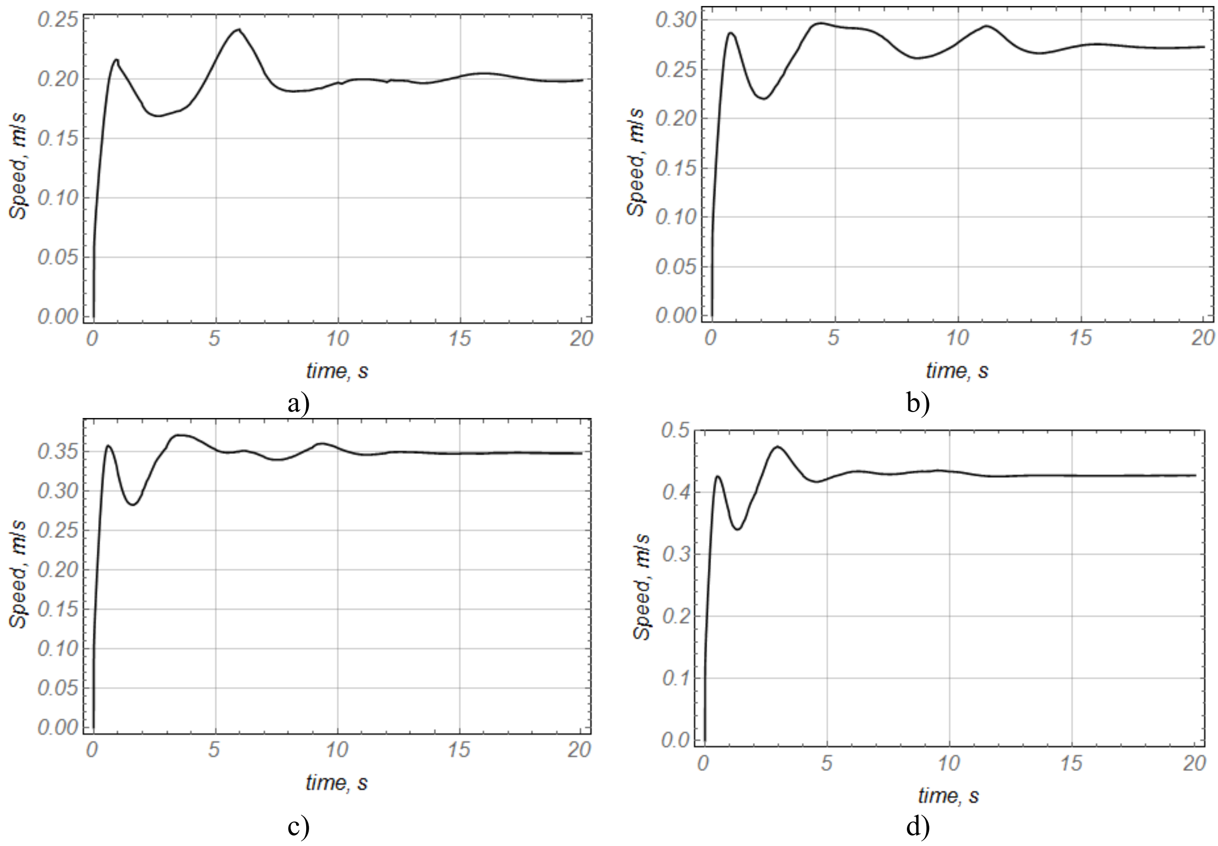


Fig. 4. Graphical dependences of the change in the average substrate velocity in the volume of the biogas reactor, in the first 20 seconds of operation, at different mixer rotation speeds: a) 30 rpm; b) 40 rpm; c) 50 rpm; d) 60 rpm.

When the speed of rotation of the mixer increases to 60 rpm (Figure 3, e), zones of high speeds appear in the upper layers of the substance, the maximum speed of which reaches values of more than 0.5 m/s. In the area between the tiers of blades and in the lower part of the tank, the flow pattern is similar to the patterns shown in (Figure 3, g) and (Figure 3, d), but with higher values of the speeds of elementary volumes of the substance. The average speed of movement of which is 0.429 m/s (Figure 4, d).

After analyzing the graphical dependencies shown in Figure 4, it is noticeable that in the first seconds of starting the mixing system, fluctuations in the average velocities of the substrate volumes occur, which have a damping character. The appearance of fluctuations is explained by the physicochemical properties of the substance, which at the beginning of mixing is in a state of rest, therefore the mixing system must overcome inertial forces to remove the substance from a state of rest and establish directed flows, the velocity vectors of which coincide with the velocity vectors of the elements of the mixing system.

The period of oscillations of the average speed for the frequency of rotation of the working body of the mixing device 30 rpm (Figure 4, a) and 40 rpm (Figure 4, b) is 15 seconds. While, for the frequency of rotation 50 rpm (Figure 4, c) and 60 rpm (Figure 4, d) is 11 seconds. In the future, a uniform established movement of elementary volumes of the substrate in the biogas reactor is observed, which is accompanied by the achievement of the mixing system of the level of working power necessary for mixing the substance.

Theoretical studies of the distribution of substance flows in a biogas reactor under the influence of a paddle mixer showed that the duration of transient modes is on average 20 seconds, regardless of the rotation speed of the mixer (Figure 4).

At the same time, on average 20 seconds is not the entire cycle of the biogas reactor, but only the period of transient motion modes (start-up modes and reaching the established motion mode). The impact of significant mechanical loads on living organisms in the fermentation process leads to the destruction of bacterial colonies and, as a consequence, a decrease in the productivity of biogas production. The period of the initial movement of the mixing device is the most loaded and energy-intensive process. Therefore, it is advisable to study and determine the amount of energy spent in transient modes (start-up mode) and steady-state motion modes of the mixing device. Also, during transient motion modes (start-up), with an increase in the rotation speed of the mixing device, the pressure on its blades increases. Accordingly, the resistance force increases and, as a result, the energy consumption of the drive motor increases. In order for the metal structure of the mixing device to withstand the loads, it is necessary to increase its mass and size characteristics. Accordingly, this increases the mass of the structure, and also increases the moment of inertia, which negatively affects the power consumption (increases power consumption).

Therefore, in order to determine the energy-efficient rotation frequency of the mixing element of the electromechanical system of biogas reactors, a study of the initial movement mode was conducted. As a result, the amount of energy spent on the starting and operating modes of the mixer was determined.

During the 3D modeling, it was assumed that the mixer reaches the nominal speed according to a linear law, the time of the output is 0.2 seconds. An array of torque data (M, Nm) was obtained for overcoming the resistance of the medium (inertia forces and friction forces) by the blades of the mixing device for different values of the angular speed of rotation of the mixer shaft (ω, rad/s). Using the Wolfram Mathematica software package, the useful power required to overcome the resistance of the medium by the mixer blades was determined.

Analysis of the results showed that at the initial moment of starting the paddle mixer with blades set at an angle of 90°, there is a sharp increase in power associated with the disturbance of the mixed medium. On average, peak values are in the range from 30 to 430 W, depending on the rotation frequency. Average operating power values are in the range from 20 to 150 W.

During the research, a pattern was found that the duration of establishing the value of the operating power of the paddle mixer required for mixing depends on the rotation frequency of its working body. Thus, at 20 rpm the duration of the transition period is 10 seconds, and at 60 rpm – 4 seconds.

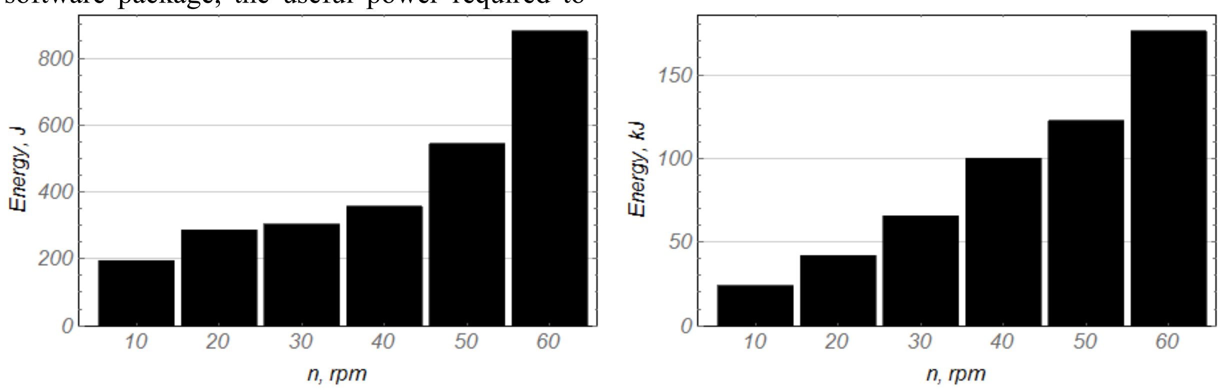
Taking into account the revealed regularities and taking into account the duration of one complete mixing cycle (20 minutes), the calculation of the useful energy consumed by the working body of the mixing device was carried out at different speeds of its rotation.

The calculation of energy consumption was carried out for mixing during the start-up period and one complete mixing cycle, according to the formula:

$$W = \sum \left(P \cdot \Delta t\right) \tag{16}$$

where P – average power over time, W; Δt – unit of time, Δt = 0.01 seconds.

The calculation results are shown in Figure 5.



a) b)

Fig. 5. Useful energy spent on mixing the substrate at different speeds of rotation of the mixing device for: a) the start-up period; b) the full mixing cycle (20 minutes).

The analysis Figure 5 allowed us to determine the percentage of the amount of useful energy required for the start-up period from the useful energy consumed during the entire mixing period (20 minutes): 10 rpm – 0.81%; 20 rpm – 0.68%; 30 rpm – 0.46%; 40 rpm – 0.37%; 50 rpm – 0.44%; 60 rpm – 0.50%.

It has been established that the dependence of the energy consumed on the increase in the frequency of rotation of the working element of the mixer corresponds to a power function $P = f(\omega^{\alpha})$.

Taking into account the graphical Figure 3, Figure 4, Figure 5 and numerical results obtained during the research, it is possible to conclude that the energy-efficient rotation frequency of a paddle-type double-deck mixer with blades installed at an angle of 90° is within 40…50 rpm. With this mode of rotation of the working body of the mixer, a uniform distribution of raw materials is ensured throughout the reactor volume; there are no turbulent speed zones that can negatively affect bacterial colonies and lead to their death [37, 38]; a combination of mass-dimensional and energy characteristics of the mixing device, taking into account the rational percentage ratio of the amount of useful energy required in transient modes (start-up) to the useful energy consumed during the mixing period (20 minutes). Such a comprehensive approach to determining the energy-efficient rotation speed of the working body of the mixing device ensures a reduction in energy consumption for mixing the substance in the reactor. Other studies conducted by us have shown that at an energy-efficient frequency (40…50 rpm), there is a reduction in energy consumption for mixing, and the average intensity of biogas output from one kilogram of organic matter has not changed.

Small biogas reactors are primarily designed for use in private homes, which are powered by a single-phase network. Therefore, it is important to use single-phase asynchronous electric motors in combination with gearboxes as the electric drive for the mixer.

CONCLUSIONS

A method for determining the energy-efficient rotation frequency of the working element of a mixing device is proposed. The method considered in the work can be used for designs of mixers and reactors of various modifications.

Pictures of trajectories of movement of elementary volumes and substrate flow velocities in three-dimensional space for a bladed double-deck mixer with blades installed at an angle of 90° were obtained. As well as graphical dependences of changes in the average substrate velocity in the volume of the biogas reactor.

The calculation of the useful energy consumed by the working body of the mixing device at different speeds of its rotation was carried out. The percentage value of the amount of useful energy required for the start-up period from the useful energy consumed for 20 minutes of mixing was determined.

The dependence of the change in the amount of energy consumed per cycle of biomass mixing, with an increase in the rotation frequency, corresponds to a power function.

A pattern has been revealed, according to which increasing the speed of the mixing device reduces the duration of the transition period at the beginning of the movement. The direction of necessary further scientific research in the modernization of not only the design of mixing systems, but also their control systems has been determined. Also, a further direction of research has been determined, which will be aimed at studying the influence of the parameters of the mixing device on substrates with different physical characteristics.

The implementation of further research will increase the energy efficiency of biogas production and the profitability of biogas processing into various types of energy.

REFERENCES

[1] Balussou, D., McKenna, R., Möst, D., & Fichtner, W. (2018). A model-based analysis of the future capacity expansion for German biogas plants under different legal frameworks. Renewable and Sustainable Energy Reviews, 96, pp. 119–131.

[2] Grando, R. L. (2017). Technology overview of biogas production in anaerobic digestion plants: A European evaluation of research and development. Renewable and Sustainable Energy Reviews, 80, pp. 44–53.

[3] Rashid, A. R., Azeem Hafiz, P. A., Muhamed, S. A., & Sharukh M. (2016). Study of Biogas as a Sustainable Energy Source in India. International Journal of Research in Mechanical Engineering, 4(3), pp. 58–62.

[4] Polishchuk, V., Valiev, T. (2023). Study of the anaerobic destruction of post-alcohol distillery waste by mateen. Machinery & Energetics, 14(2), pp. 60-69.

[5] Polishchuk, V. M., Shvorov, S. A., Krusir, G. V., Derevianko, D. A., Dvornyk, Ye. O., & Davidenko, T. S. (2021). Increased biogas output during fermentation of manure of cattle with winemaking waste in biogas plants. Machinery & Energetics, 12(4), pp. 67-76.

[6] Polishchuk, V. M., Derevianko, D. A., & Dvornyk, Ye. O. (2021). Efficiency of production and application of solid fuels in rural areas. Machinery & Energetics, 12(1), pp. 31-38.

[7] Polishchuk, V. M., Derevianko, D. A., Tarasenko, S. Ye., & Antypov, Ye. O. (2021). Study of

Efficiency of Wet Cleaning of Biodiesel. Machinery & Energetics, 12(3), pp. 63-75.
[8] Vimmerstedt, L., Brian, J., Bush, W., Hsu, D. D., Inman, D., & Peterson, S. O. (2015). Maturation of biomass-to-biofuels conversion technology pathways for rapid expansion of biofuels production: a system dynamics perspective. Biofuels, Bioproduct and Biorefining, 9, pp. 158–176.
[9] Zulauf, C., Prutska, O., Kirieieva, E., & Pryshliak, N. (2018). Assessment of the potential for a biofuels industry in Ukraine. Problems and Perspectives in Management, 16(4), pp. 83–90.
[10] Svitlychnyi, O., Havrylyuk, O. (2021). Current state of activity of public governance bodies in the field of waste management. Law. Human. Environment, 12(3), pp. 112-118.
[11] Kukhar, O. (2021). Theoretical and legal definition of the concept of "agricultural waste". Law. Human. Environment, 12(1), pp. 75-84.
[12] Scarlat, N., Dallemand, J.-F., & Fahl, F. (2018) Biogas: Developments and perspectives in Europe. Renewable Energy, 129, pp. 457–472.
[13] Zhuravel, Y., Artemenko, O., Lytvyn, N., Yara, O., & Uliutina, O. (2023). International experience in the use of alternative energy sources (within the European Union). Law. Human. Environment, 14(3), pp. 46-59.
[14] WBA (2019). Global Potential of Biogas; World Biogas Association: London, UK.
[15] EBA (2019). EBA Statistical Report 2019; European Biogas Association: Brussels, Belgium.
[16] EBA (2023). EBA Statistical Report 2023; European Biogas Association: Brussels, Belgium.
[17] Kaplun, V., Osypenko, V., & Makarevych, S. (2022). Forecasting the electricity pricing of energy islands with renewable sources. Machinery & Energetics, 13(4).
[18] Hatsenko, K. V.; Voloshin, N. D. (2019). Technology of biogas production on the basis of food waste. Collection of scientific works of the Dnipro State Technical University (technical sciences), 1(34). pp. 131-136.
[19] Janczak, D., Mazurkiewicz, J., Czekała, W., Myszura, M., Kozłowski, K., & Jeżowska, A. A. (2019). Possibility of Functioning Biogas Plant at a Poultry Farm. Journal of Ecological Engineering, 20(11), pp. 225-231.
[20] Deublein, D., Steinhauser, A. (2008). Biogas from Waste and Renewable Resources. An Introduction. KGaA, Weinheim, 450 p.
[21] Ward, A. J., Hobbs, P. J., Holliman, P. J., & Jones D. L. (2008). Optimisation of the anaerobic digestion of agricultural resources. Bioresource Technology, 99, pp. 7928-7940.
[22] Holub, S., Shinkaruk, N. (2021). Principles of legal regulation of bioenergy use in the European Union. Law. Human. Environment, 12(4), pp. 72-77.
[23] Novak, T., Dudash, M. (2023). Stimulating the development of entrepreneurship in rural areas: Theoretical-legal characteristics. Law. Human. Environment, 14(2), pp. 65-80.
[24] Danylyshyn, V., Koval, M. (2022). Development of alternative energy in the world and Ukraine. Machinery & Energetics, 13(2), pp. 50-61.
[25] Latha, K., Velraj, R., Shanmugam, P. & Sivanesan, S. (2019). Mixing strategies of high solids anaerobic co-digestion using food waste with sewage sludge for enhanced biogas production. Journal of Cleaner Production, 210, pp. 388–400.
[26] Foukrach, M., Bouzit, M., & Ameur, H. (2020). Effect of Agitator's Types on the Hydrodynamic Flow in an Agitated Tank. Chinese Journal of Mechanical Engineering. 33. 37 p.
[27] Ameur, H. (2016). Mixing of complex fluids with flat and pitched bladed impellers: effect of blade attack angle and shear-thinning behavior. Food and Bioproducts Processing, 99, pp. 71-77.
[28] Teleszewski, T. J., Zukowski, M. (2018). Analysis of Heat Loss of a Biogas Anaerobic Digester in Weather Conditions in Poland. Journal of Ecological Engineering, 19(4), pp. 242–250.
[29] Pham, C. H., Vu, C. C., Sommer, S. G., & Bruun, S. (2014). Factors Affecting Process Temperature and Biogas Production in Small-scale Rural Biogas Digesters in Winter in Northern Vietnam. Asian-Australasian Journal of Animal Sciences, 27(7), pp. 1050-1056.
[30] Marks, S., Dach, J., Fernandez, M. F. J., Mazurkiewicz, J., Pochwatka, P., & Gierz, Ł. (2020). New Trends in Substrates and Biogas Systems in Poland. Journal of Ecological Engineering, 21(4), pp. 19-25.
[31] Chervonyi, I. F., Kuris, Yu. V. (2010). Biogas technologies: monograph, ZDIA, 493 p.
[32] Ratushnyak, G. S., Lyalyuk, O. G., & Koshcheev, I. A. (2017). Biogas plants with renewable energy sources for thermal stabilization of biomass fermentation: monograph. VNTU, 188 p.
[33] Lunyaka, K. V., Vus, D. N., Rusanov, S. A., & Klyuev, O. I. (2009). Dissolution of solids with stirring with stirrers in vessels with vertical partitions. Theory and practice of modern natural science. 36-39.
[34] Zakomorny, D. M., Povodzinsky, V. M., & Shibetsky, V. Yu. (2015). Classification and analysis of fermenters with mechanical mixing devices in aerobic processes of biotechnology. ScienceRise, 5(2), pp. 24-32.
[35] Mykola, Z., Mykhailo, S. (2020). Mathematical Model of Thermal Processes During the Fermentation of Biomass in a Biogas Reactor. 2020 IEEE KhPI Week on Advanced Technology (KhPIWeek), pp. 227-231.
[36] Gorji, M., Bozorgmehry Boozarjomehry, R. and Kazemeini, M. (2007). CFD Modeling of Gas-Liquid Hydrodynamics in a Stirred Tank Reactor. Iranian Journal of Chemistry and Chemical Engi-

neering, 26(2), pp. 85-96. doi: 10.30492/ijcce.2007.7657

[37] Rathore, A. S., Kanwar Shekhawat, L., Loomba, V. (2016). Computational fluid dynamics for bioreactor design. Bioreactors. Wiley. pp. 295-322. doi:10.1002/9783527683369.ch10

[38] Verma, R., Mehan, L., Kumar, R., Kumar, A., Srivastava, A. (2019). Computational fluid dynamic analysis of hydrodynamic shear stress generated by different impeller combinations in stirred bioreactor. Biochem Eng J. p. 151. doi: 10.1016/j.bej.2019.107312

[39] Huang, W., & Li, K. (2013). CFD Simulation of Flows in Stirred Tank Reactors Through Prediction of Momentum Source. In Tech. doi: 10.5772/51754

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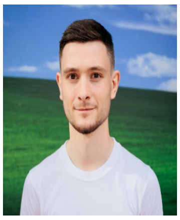

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