The anaerobic method of treating wastewater from biotechnological and economic industries has great prospects for the development of a renewable energy source. Biogas released during the operation of the bioreactor can be used as an energy source for the generation of electricity and heat.

This paper reports the design of an apparatus for wastewater treatment with microorganisms immobilized on inert carriers. The original substrate supplied to the bioreactor is heated by thermostating. The temperature of the original substrate is controlled using an electronic temperature meter. Temperature in the bioreactor is also controlled; maintaining the methane growth of microorganisms in the range of 35–37 °C is enabled by a temperature sensor. The gas that is released during the experiment is collected in a gas collector, where its volume is measured, owing to the torn cylinder connected to the gas collector. Additionally, a temperature sensor is installed in the gas collector to determine the mass of the biogas collected in the experiments. Owing to the high-speed camera connected to a computer, the process of formation and separation of gas bubbles from the biofilm is recorded, as well as the thickness of the biofilm on flat carriers. To determine the effect of hydrodynamics under a laminar mode of wastewater supply, in the bioreactor channels, a peristatic dosing pump is used in the experimental installation. In the experiments, the thickness of the biofilm changed in the range from 10^{-3} m to $4.8 \cdot 10^{-3}$ m and, because of this, the width of the channel along which the substrate flow moved changed accordingly.

Experimentally, it was established that the volume of biogas released increases with an increase in the rate of wastewater in the bioreactor channels. Based on the experimental results, a criterion equation was built using which can determine the coefficient of mass yield

Keywords: biogas production, influence of hydrodynamics on mass transfer, wastewater, flat carriers

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DETERMINING THE INFLUENCE OF WASTEWATER HYDRODYNAMICS IN BIOREACTORS ON THE PROCESS OF MASS TRANSFER

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1. Introduction

Rapid population growth and industrialization are leading to environmental change. Environmental pollution is a growing danger that worries the whole world, as well as its impact on the world's ecosystem. One of the most important natural resources for life is water. Large volumes of wastewater resulting from human activity and industrial production accompany the disposal system in the form of municipal wastewater, or industrial wastewater. Wastewater enriched with various polluting organisms is harmful to aquatic flora and fauna and, due to accumulation in the soil, leads to a decrease in the productivity of growing crops. Solving this issue in the usual way, that is, by laying multi-kilometer sewage collectors to all enterprises, is very unprofitable and could lead to the leakage of wastewater into the soil [1].

Wastewater treatment involves four stages of purification. Pre-cleaning (mechanical) implies the removal of large and solid particles. The second stage is primary treatment, which enables the removal of organic and inorganic solids through a physical process, and the resulting runoff is called primary. The third stage of treatment is called secondary purification; it includes the biological degradation of organic compounds and substances left over from the primary treatment. And, finally, the tertiary purification, which usually occurs owing to a chemical process that very often involves residual disinfection. Removal of organic matter from wastewater can be carried out by various biological methods [2].

The practice of wastewater treatment shows that the most effective for this type of wastewater is biological treatment. Biological wastewater treatment includes anaerobic and aerobic processes. The anaerobic cleaning method, unlike aerobic, avoids air pollution by microbial aerosols, so the pretreatment of contaminated water in a sealed reactor is extremely beneficial for the environment. Anaerobic methods of wastewater treatment differ from aerobic ones in that 90 % of organic compounds are converted into metabolic products, the main component of which is a valuable energy carrier – methane, and only 10 % are converted into biomass. This predetermines the prospects of using anaerobic methods of industrial wastewater treatment [1]. Biogas can be used as an energy source for the generation of electricity and heat [3].

The performance of bioreactors depends on the efficiency of use of biological agents, which depends on the conditions of the process. One of the ways to increase the performance of fermentation is cell immobilization, which enables the possibility of continuous processing, cell stability, reducing the cost of recovery, disposal, and subsequent processing. Immobilization of cells protects them from shear forces that may arise during the operation of the bioreactor. Depending on the location of cell units, three types of reactors can be distinguished: with suspended particles, with fixed particles, and with moving surfaces used with immobilized cells [4].

Despite the number of proposed devices for water purification systems, there are still no perfect designs of anaerobic bioreactors that would fully meet the needs of production.

Hydrodynamics affects the contact of microorganisms with the carrier, the place of biofilm development, as well as the physical properties of the biofilm, such as the density and strength of adhesion to the carrier. Therefore, it is a relevant task to focus scientific and practical work on studying the hydrodynamic processes of mass transfer that affect the performance of the bioreactor.

2. Literature review and problem statement

Anaerobic biological treatment is a more economical way to purify water [5] and is also a renewable energy source [6]. Organic matter is broken down through various stages of biological decomposition into methane (CH_4), carbon dioxide (CO_2), hydrogen sulfide (H_2S), and formed sludge, which can be used as fertilizer for the soil [7]. In article [8], the basic principles and methods of the anaerobic fermentation process were considered. The authors determined that hydrolysis is the limiting stage of the complex process of degradation of organic compounds. Therefore, to accelerate the conversion and production of biogas, it is necessary to use pretreatment of wastewater to improve hydrolysis that limits the speed. Anaerobic fermentation can occur not only in agricultural emissions rich in organic materials [9] but in microalgae as well [10]. The authors of [11] proposed the release of methane using membrane elements to reduce the cost of biogas purification. Although the main disadvantage of membrane separation is many stages, the process of methane release is more economical than the process of removing impurities with the production of methane.

However, the problems related to the introduction of anaerobic fermentation have become the main obstacle for this source to become a leading renewable energy source. Among these issues are low volumetric biogas yields and difficulties associated with the stability of large-scale continuous operation [12, 13].

Investigating the process of anaerobic fermentation was considered in [14, 15] as a two-stage process. First, acidogenic bacteria convert glucose to acetate, then methanogenic bacteria turn this acid into methane and carbon dioxide – biogas. Work [1] states that in the process of anaerobic decomposition of organic matter, three main stages should be distinguished, which occur under the influence of three physiological groups of bacteria: enzymatic hydrolysis, acid formation, and methanogenesis. In [16], four stages of anaerobic fermentation were distinguished: acidogenesis, acetogenesis, and methanogenesis. There is an assumption that there can be five stages of anaerobic decomposition, namely: disintegration, hydrolysis, fermentation (fermentation), acetogenesis, and methanogenesis [1]. To simplify the modeling of the process of degradation of organic compounds, a two-stage model is used.

The first stage of the process, which is carried out by acidogenic biomass, is hydrolysis and acid formation [17]:

$$C_6H_{12}O_6+2H_2O\rightarrow 2CH_3COOH+4H_2+2CO_2.$$

The second stage is acetate methane formation, which occurs as a result of the vital activity of methanogens [17]:

$$CH_3COOH\rightarrow CH_4+CO_2.$$

Works [18, 19] report the results of studies into methane biosynthesis processes and their practical implementation, which show that in anaerobic biofilters the intensity of gas formation is much higher than in bioreactors with free-floating methanogenic microflora. Immobilization of methanogenic microflora on carriers makes it possible to increase their concentration and contributes to the intensification of anaerobic fermentation. Immobilization in the form of a biofilm on fixed carriers has several advantages compared to other methods of containing microflora [20, 21]. To enable a stable supply of the substrate to the surface of the biofilm and the removal of biogas, it is necessary to create a favorable hydrodynamic environment in the bioreactor, which will provide high mass transfer coefficients in the boundary layer of liquid near the surface of the biofilm.

Studies [22, 23] were carried out to determine the role of hydrodynamics on the structure of biofilm in the system of continuous recirculation of cultivation. Biofilms were grown under laminar and turbulent flow in parallel glass flow tanks. The results showed no difference between the types of biofilms. However, process conditions had a greater impact on the structure of the biofilm. Biofilms grown in a turbulent stream consisted of filamentous streamers while those grown in a laminar stream consisted of a monolayer of cells interspersed with annular microcolonies. Subsequent studies [24, 25] considered the rate of diffusion transport of the substrate, nutrients, and gases, determined by the physiology of populations at different depths of biofilm thickness. Thus, the diffusion of these substances through the biofilm can control the growth of microorganisms deep in the biofilm. The ability to purify by a particular population depends on the concentration of biomass in the biofilm. In equilibrium, the maximum biomass density is a function of the concentration of the limiting substrate that is currently present in wastewater. Thus, different microbial populations may arise as a result of different composition of the substrate. The concentration gradient caused by diffusion resistance determines the distribution of organisms along the thickness of the biofilm. Consequently, the degree of mixing, which corresponds to turbulence in the immediate vicinity of the biofilm, becomes the controlling element at this stage since it directly affects the thickness of the stagnant zone. However, the researchers did not determine the limiting stage of diffusion, in which the main diffusion resistance is concentrated during the two-dimensional movement of the fluid.

The authors [26, 27] determined that the hydrodynamic situation in the bioreactor plays an important role in shaping the structure of the biofilm. Under a laminar mode, a conditionally anisotropic biofilm is formed. Under a powerful unidirectional hydrodynamic stress, cell aggregates are threaded along the flow direction with the formation of "tapes", which are attached to the surface at one end and the other can fluctuate freely in the stream. Hydrodynamics affects the contact of microorganisms with the carrier, the place of development of the biofilm, as well as the physical properties of the biofilm, such as the density and strength of adhesion to the carrier. Biofilms that grow under strong hydrodynamic loads are thinner and denser than those exposed to lower hydrodynamic loads. Therefore, in the development of the model structure of the device, it is necessary to provide a laminar mode for feeding the substrate.

Studies were reported in [28, 29] to find a practical way to evaluate the operation of bioreactors but they did not make it possible to evaluate the performance of bioreactors in terms of kinetic coefficients and mathematical modeling. Moreover, other studies [30, 31] focused only on the calcu-

lation of critical kinetic coefficients and the calculation of purification efficiency. In addition, the process of supplying the substrate from the liquid flow nucleus to the laminar boundary layer in contact with the biofilm was not investigated or evaluated.

All this suggests that it is expedient to conduct a study on determining the effect of hydrodynamics of wastewater in bioreactors on the mass transfer process, as a result of which biogas is obtained. In accordance with these studies, it will be possible to investigate the mass exchange processes occurring in the bioreactor.

3. The aim and objectives of the study

The aim of this study is to determine the effect of hydrodynamics of wastewater in bioreactors on the mass transfer process, as a result of which biogas is obtained. This will make it possible to calculate the size of the anaerobic bioreactor and simulate the operation of the device to determine its power.

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

– to design a model structure of the apparatus for wastewater treatment with microorganisms immobilized on inert carriers;

– to determine theoretical and experimental indicators of the volume of biogas released and the coefficient of mass yield.

4. The study materials and methods

Experimental and practical studies into the influence of hydrodynamics on the process of mass transfer were carried out in a bioreactor designed for wastewater treatment with microorganisms immobilized on inert carriers. They were conducted at the experimental laboratory of heat and mass transfer processes at the Department of Biotechnics and Engineering of the Faculty of Biotechnology and Biotechnics of the National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute" (Ukraine). In addition, the laboratory installation was introduced into the educational process.

The object of this research is the process of biogas production in a bioreactor, which was made of a transparent material to visualize the process of biogas formation. In addition, before the experiment, the installation was blown with nitrogen to create conditions for the anaerobic process.

The subject of the research is the influence of hydrodynamics on the process of mass transfer in a bioreactor. Using a peristaltic dosing pump, the flow rate of the substrate changed, thereby altering the speed in the bioreactor channels. In the experiments, the thickness of the biofilm changed and, because of this, the width of the channel along which the substrate flow moved changed accordingly.

Studies were carried out at an experimental installation in which, as a substrate for modeling the process, a glucose solution was taken. The initial concentration of the substrate in the experiments was the same and was equal to 1 % (wt.). As biomass, active sludge was used, which was applied to an inert carrier – a substrate. Constant supply of the solution (under a laminar mode) of glucose (substrate) to the bioreactor is enabled by the use of the VELP SP 311/12 peristaltic pump (Italy) – a single-channel pump with adjustable flow rate. It enables volumetric supply of model fluid to the bioreactor, from $8.917 \cdot 10^{-7}$ m^3/s to $6.6 \cdot 10^{-6}$ m^3/s.

In the experimental bioreactor, it was necessary to maintain the mesophilic mode of operation, namely at 35–37 °C. To maintain the required temperature in the installation, the method of biomass thermostating is used, regardless of the external temperature. To do this, a heat exchanger is used to which a liquid heated to 40–42 °C is supplied from the thermostat LOIP LT-211a. The LOIP ATC control system adapts the parameters of the thermostat PID controller to the type of working fluid and eliminates the effect of air temperature instability on the system operation.

The structure of the bioreactor was built with a planar approximate load, which enables uniform distribution of the substrate and, as a result, more complete use of the usable volume of the bioreactor. This type of bioreactor makes it possible to organize almost equivalent conditions for mass transfer over the entire surface of the biofilm. The substrate was fed into the bioreactor by an upward flow in order to reduce the removal of active biomass from the reactor.

Temperature control and adjustment in the bioreactor was enabled by a temperature sensor for measurement accuracy. Mercury thermometers were also used to control the temperature of the original substrate to the reactor and the gas temperature in the gas collector.

The measurement results and graphical representation of experimental data were treated using standard statistical software Microsoft Excel 2010 (USA).

5. Results of studies into the influence of hydrodynamics on the process of mass transfer

5. 1. Designing a model structure of the apparatus for wastewater treatment with microorganisms immobilized on inert carriers

A model structure of the installation for the study of mass transfer processes in a bioreactor was designed, which is shown schematically in Fig. 1. The main apparatus of the installation is bioreactor 1. It belongs to the type of bioreactors with ascending flow and vertical flat partitions 2. To visualize the processes that occur in the bioreactor, it is made of optically transparent polystyrene. Bioreactor 1 has lid 3, which hermetically closes the container using seal. The bioreactor is equipped with sensors to measure pressure 4 and temperature 5. With increasing pressure in the bioreactor, a safety valve B_1 is placed on lid 3. During the anaerobic process in the bioreactor, biogas is released, which enters the gas collector 6, which is filled with liquid. Gas collector 6 is connected by an elastic polymer tube with a perforated cylinder 7 using a water seal, which makes it possible to determine the volume of biogas collected. To control the pressure in the gas collector 6, a pressure sensor 4 is installed.

The temperature for methanogenic growth of microorganisms under a mesophilic mode of operation of the bioreactor is maintained within 35–37 °C by thermostating. To do this, the heat exchanger 9 is used, which is connected to thermostat 10. Owing to the injection pump of thermostat 10, effective mixing of the heat carrier and high accuracy of maintaining the temperature in the closed-loop heat exchanger 9 are enabled. To control the feed rate of the substrate to the reactor, a dosing perillstatic pump 11 is installed, which is equipped with a flow meter 12. Temperature control of the initial substrate supplied to the bioreactor from capacity 8 is carried out using an electronic temperature meter 5.

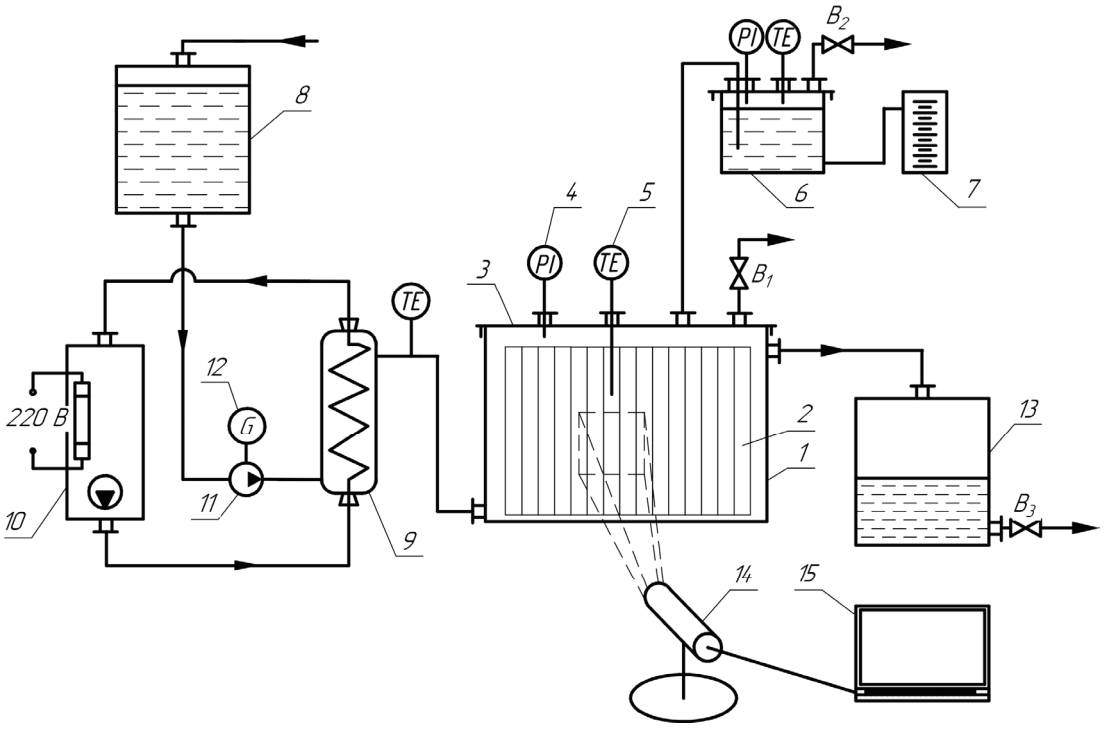

Fig. 1. Experimental installation for the study of mass transfer in the anaerobic process of biogas production: 1 — bioreactor; 2 — fixed carriers for biomass immobilization; 3 — hermetically sealed lid; 4 — pressure sensor; 5 — temperature sensor; 6 — gas collector; 7 — perforated cylinder; 8 — container for the original substrate; 9 — heat exchanger; 10 — thermostat; 11 — perillstatic pump; 12 — flow meter; 13 — container for the used substrate; 14 — high-speed digital camera; 15 — personal computer; B_1 and B_2 — valves for gas

Before starting operation, bioreactor 1 is blown with nitrogen for 5 minutes to enable anaerobic conditions. To this end, the installation opens valve B_1 on the lid of the bioreactor and B_2 on the gas collector.

With the help of a high-speed digital camera 14 connected to a personal computer, the following are recorded:

– the process of biogas release;

– the process of formation of gas bubbles;

– hydrodynamic processes occurring in the bioreactor.

During the experiment, the following process parameters were measured:

– wastewater flow rate;

– the temperature of wastewater at the inlet to the bioreactor and inside it;

– biogas pressure and temperature;

– volume of biogas released;

– duration of the experiment.

5. 2. Theoretical and experimental indicators of the volume of biogas released and the mass yield coefficient

Experimental studies into the process of influence of hydrodynamics on the efficiency of the mass transfer process in the experimental apparatus were carried out to establish the main parameters of the process to obtain initial data on further calculations of the apparatus.

Biofilm is placed in the anaerobic bioreactor, which is located on fixed carriers in the form of flat vertical sheets that form channels. Through these channels, an upward stream moves wastewater, in which the substrate is dissolved – glucose. The hydrodynamic conditions in the bioreactor channels are the same since their geometry and fluid input conditions are preserved. The speed of movement of wastewater in the channels based on the law of continuity of fluid flows, m/s [31]:

$$W_W = \frac{V_P}{LB - (2\delta_{BF} + \delta_C) b_C n_C}, \quad (1)$$

where V_P – pump capacity or volumetric wastewater consumption, m^3/s;

L, B – length and width of the bioreactor, m;

b_C, δ_C – width and thickness of biofilm carrier, m;

n_C – number of biofilm carriers;

δ_{BF} – biofilm thickness, m.

In the channel, there is a flat flow of liquid whose hydrodynamics is described by the Reynolds criterion [32], in which the linear size is ($Z–2\delta_{BF}$):

$$\mathrm{Re} = \frac{W_W (Z - 2\delta_{BF})}{\upsilon}, \quad (2)$$

where Z is the distance between the sheets that form the channel, m;

υ – coefficient of kinematic viscosity of wastewater, m^2/s.

The value of the Reynolds criterion in all experiments was within (0.417÷1.888), that is, there was a laminar movement of fluid.

Biomass in an anaerobic bioreactor is fixed on fixed carriers of a constant surface, which take the form of plates. The thickness of the biofilm on the carrier, m:

$$\delta_{BF} = \frac{G_{BF}}{2 b_C h_C n_C \rho_{BF}}, \quad (3)$$

where G_{BF} is mass of biofilm on carriers, kg;

h_C – height of biofilm carrier, m;

ρ_{BF}=1275 kg/m^3 – biofilm density.

The volume of dry biomass in biofilm, kg:

$$G_{BM} = \overline{X_B} G_{BF}, \quad (4)$$

where $\overline{X_B} = 0.37(\text{mass})$ is the dry biomass content in biofilm.

Using equations (1) to (3), values were calculated that depend on the performance of the pump, given in Table 1.

Table 1

Calculation results related to pump performance

Experiment No.	1	2	3	4	5	6	7	8	9
$V_C \cdot 10^{-6}$, m^3/s	0.892	1.55	2.08	2.83	3.58	4.33	4.83	5.83	6.6
$W_W \cdot 10^{-4}$, m/s	0.30	0.59	0.96	1.54	1.91	2.45	3.18	3.98	5.66
Re	0.42	0.69	0.95	1.18	1.43	1.63	1.77	1.88	1.88
$\delta_{BF} \cdot 10^{-3}$, m	1.00	1.71	2.43	3.24	3.30	3.60	4.00	4.30	4.80

Table 1 demonstrates that with an increase in the rate of supply of the substrate to the reactor, the biofilm grows accordingly. Since with each subsequent experiment the thickness of the biofilm increases, then, accordingly, mass transfer takes place faster.

During the experiment, the volume of gas formed during the fermentation process was determined. The mass of biogas collected in the experiment is determined on the basis of the Mendeleev-Clapeyron law [33], according to the formula, kg:

$$G_{BG} = \frac{V_{BG}\left(P_{AP} + \Delta P_{BG}\right)}{R} \times \times \frac{M_{CH_4} y_{CH_4} + M_{CO_4}\left(1 - y_{CH_4}\right)}{273 + t_{BG}}, \quad (5)$$

where V_{BG} is the volume of biogas collected during the experiment, m^3;

P_{AP} – atmospheric pressure, Pa;

ΔP_{BG} – overpressure of biogas in the gas collector, Pa;

R=8,310 J/(kmol·K) – universal gas constant;

M_{CH4}, M_{CO4} – molecular weights of methane and carbon dioxide, kg/kmol, respectively;

y_{CH4}=0.7 – molar content of methane in biogas;

t_{BG} – biogas temperature in the gas collector, °C.

The hydrolysis rate constant is determined by the equation given in [26], h^{-1}:

$$k = -\frac{\ln\left(1 - \frac{G_{BGi}}{G_{BG\max}}\right)}{\tau}, \quad (6)$$

where G_{BGi} is the mass of biogas collected in the experiment, kg;

$G_{BG\max}$ is the mass of biogas collected in the last experiment, kg;

τ – duration of the experiment, hour.

Fig. 2 shows the dependence of the mass of the collected biogas on the duration of the experiment at different rates of wastewater in the bioreactor channels.

The results (Fig. 2) show that the volume of biogas released increases with increasing experiment time. This serves as evidence that the concentration of microorganisms in the biofilm responsible for the degradation of organic impurities is small and develops slowly since it takes time to adapt. This phase is called lag. Then there is a rapid increase in cell concentration, which is called the growth phase. The growth phase ends, and the stationary phase begins [26, 27].

The increase in the volume of biogas released with an increase in the rate of wastewater in the bioreactor channels is caused by the movement of the substrate (glucose) from the liquid flow to the laminar boundary layer. In this layer, mass transfer occurs due to molecular diffusion, which is mainly carried out due to convective diffusion. Consequently, with an increase in the rate of wastewater, the process of convective diffusion intensifies. This can be seen in Fig. 3, which shows the dependence of the specific average bioreactor performance on biogas on the rate of wastewater:

$$m = \frac{\sum_{i=n}^{i=1} G_{B_i}}{n\tau f}, \quad (7)$$

where n=12 is the number of experiments;

$f = 2b_C h_C n_C$ – surface area of the biofilm, m^2.

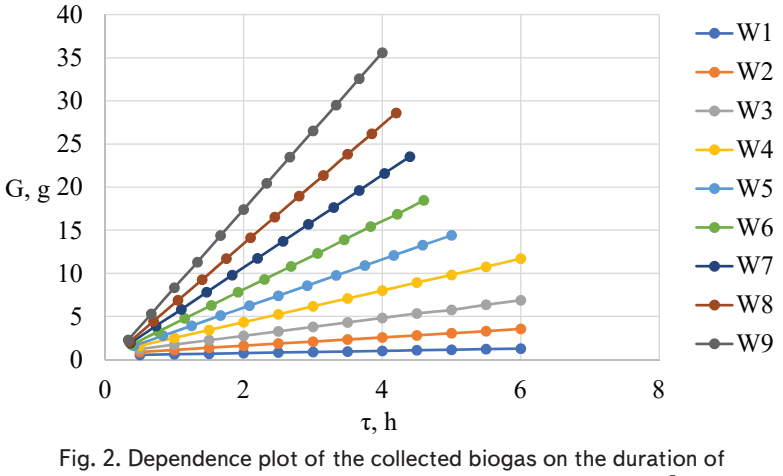

Fig. 2. Dependence plot of the collected biogas on the duration of the experiment at different speeds of wastewater: W1=3·10^{-5} m/s; W2=5,86·10^{-5} m/s; W3=9,58·10^{-5} m/s; W4=1,54·10^{-4} m/s; W5=1,91·10^{-4} m/s; W6=2,45·10^{-4} m/s; W7=3,18·10^{-4} m/s; W8=3,98·10^{-4} m/s; W9=5,66·10^{-4} m/s

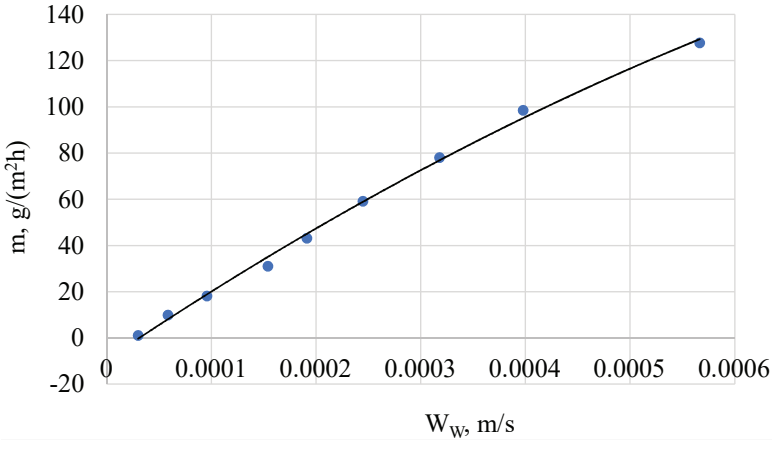

Fig. 3. Polynomial dependence plot of the specific performance of bioreactor for biogas on the rate of wastewater with the value of approximation reliability R^2=0.9972

With a two-dimensional movement of wastewater in the channel formed by the sheets of the biofilm carrier, there are two types of mass transfer:

– convective diffusion in the nucleus of the flow;

– molecular diffusion in the boundary flow layer of the biofilm.

Since the coefficient of convective diffusion is an order of magnitude greater than the coefficient of molecular diffusion, the limiting stage can be considered mass transfer in the boundary wall layer, in which the main diffusion resistance is concentrated. That is, at $\frac{1}{m\beta_y} << \frac{1}{\beta_x}$, a mass transfer coefficient can be taken approximately equal to the coefficient of mass transfer [32]:

$$K_x \approx \beta_x. \quad (8)$$

Knowing the volume of biogas released, it is possible to calculate the coefficient of mass yield, mol/(m^2·*h*) [32]:

$$\beta_x = \frac{m_{BG}}{f(X_{SB} - X)}, \quad (9)$$

where m_{BG} is the molar performance of bioreactor for biogas, mol/h:

$$m_{BG} = \frac{\sum_{i=n}^{i=1} G_{B_i}}{n\tau} \frac{1}{M_{BG}},$$

where M_{BG} is the molecular weight of biogas, g/mol, where:

$$M_{BG} = M_{CH4} y_{CH4} + M_{CO2}(1 - y_{CH4}),$$

X_{SB} is the molar concentration of acetic acid at the phase separation boundary, where:

$$X_{SB} = \frac{\sum_{i=n}^{i=1} G_{A_i}}{M_A} \frac{M_{H_2O}}{G_{H_2O}},$$

G_{Ai} is the mass of acetic acid, g;

M_A – molecular weight of acetic acid, g/mol;

M_{H_2O} – molecular weight of water, g/mol;

G_{H_2O} – mass of wastewater, g;

X – molar concentration of the substrate:

$$X = \frac{\sum_{i=n}^{i=1} G_{S_i}}{M_S} \frac{M_{H_2O}}{G_{H_2O}},$$

G_{Si} is the mass of substrate (glucose), g;

M_S – molecular weight of the substrate, g/mol.

Fig. 4 shows a dependence plot of the coefficient of mass yield on the Reynolds criterion $\beta_x = f(\mathrm{Re})$. The plot (Fig. 4) demonstrates that with an increase in the value of the Reynolds criterion, the coefficient of mass yield increases. This dependence can be determined using regression analysis and described by an empirical equation:

$$\beta_x = 4 \cdot 10^{-5}\, \mathrm{Re}^{1,45}. \quad (10)$$

The standard error of equation (10) from the constructed polynomial plot (Fig. 4) according to the experiment is 12 %.

Knowing the coefficient of mass yield, it is possible to determine the Nusselt diffusion criterion [34]:

$$Nu_x = \frac{\beta_x \delta_{BL}}{D_x}, \quad (11)$$

where D_x is the molecular diffusion coefficient, m^2/s [33]:

$$D_x = 7.4 \cdot 10^{-12} \frac{(\beta M_{H_2O})^2 T}{\mu V^{0.6}},$$

where β is a parameter that takes into consideration the association of water molecules;

T – wastewater temperature, K;

μ – dynamic viscosity of wastewater, mPa·s;

V – molar volume of the substrate (glucose, cm^3/mol);

δ_{BL} – thickness of the laminar boundary layer, m [32]:

$$\delta_{\Pi} = \left(\frac{D_x}{\nu_x}\right)^{0.5} 0.5\delta_{BF}, \quad (12)$$

where ν_x is the coefficient of kinematic viscosity of water, m^2/s.

The value of Prandtl's diffusion criterion [32]:

$$\mathrm{Pr}_x = \frac{\mu_x}{\rho_x D}, \quad (13)$$

where μ_x is the coefficient of dynamic viscosity of water, Pa·s.

According to calculations on the experimental data values of the criteria of Nusselt, Reynolds, and Prandtl, using regression analysis, a criterion equation was derived by which the mass yield coefficient can be determined. The equation is:

$$Nu_x = 1.94\, \mathrm{Re}^{2.19}\, \mathrm{Pr}_*^{0.01}. \quad (14)$$

The process of supplying the substrate from the flow nucleus to the laminar boundary layer has a large diffusion resistance where the process of mass transfer of the substrate to the biofilm takes place. Therefore, this process is limiting when obtaining biogas.

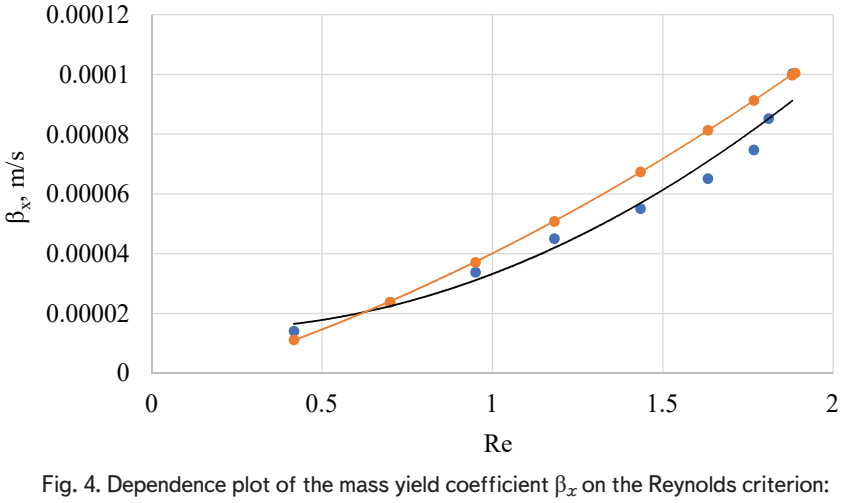

Fig. 4. Dependence plot of the mass yield coefficient β_x on the Reynolds criterion: ● – experiment; ● – power function (10); —·— – polynomial plot of the experiment with the value of approximation reliability R^2=0.9914; — – plot of empirical equation (10)

6. Discussion of results of investigating the influence of hydrodynamics on the process of mass transfer

The designed model structure of the device (Fig. 1) makes it possible to study the effect of hydrodynamics on the process of mass transfer in a bioreactor intended for wastewater treatment with microorganisms immobilized on inert carriers. The proposed innovative solution when designing a model structure of the device has made it possible to improve the temperature control system, to control the substrate feed rate, as well as to investigate the hydrodynamic processes of water moving in the bioreactor channels. As a substrate supplied to the apparatus, a glucose solution of 1 % (w) was taken to simulate the process. A bioreactor with an upward flow and vertical flat inert carriers on which active sludge was immobilized was modeled. The reactor maintained a mesophilic regime for the favorable operation of biomass or methanogens in active sludge. It was also very important to provide a laminar mode of substrate supply to the reactor, for better growth and reducing the separation of activated sludge from inert carriers. Therefore, to enable this mode, the VELP SP 311/12 11 perillstatic pump, which is equipped with a flow meter 12, was used. It provides volumetric supply of model fluid to the bioreactor at speeds from $8.917 \cdot 10^{-7}$ m^3/s to $6.6 \cdot 10^{-6}$ m^3/s. Due to the placement in the installation of such a pump, it was possible to change and measure the rate of supply of the ascending substrate to the bioreactor in the experiments.

Owing to the thermostating method, the methanogenic growth of microorganisms is maintained when operating under a mesophilic mode of bioreactor operation. For this purpose, a heat exchanger 9 is used, to which liquid heated to 40–42 °C is supplied from the LOIP LT-211a 10 thermostat. The LOIP ATC control system adapts the parameters of the thermostat PID controller to the type of working fluid and eliminates the effect of air temperature instability on the system operation. Owing to the injection pump of the thermostat LOIP LT-211a 10, efficient mixing of the heat carrier and high accuracy of maintaining the temperature in the closed-loop heat exchanger 9 are enabled. Temperature control of the initial substrate supplied to the bioreactor from capacity 8 is carried out using an electronic temperature meter 5.

During the operation of the bioreactor, biogas is released, which entered the gas collector 6, which is filled with liquid. It is equipped with a pressure sensor 4, a temperature meter of 5 and valve B_2 for emergency release of biogas or the ability to enable anaerobic operation of the installation before starting its work. Owing to the water seal, the gas collector is connected by an elastic polymer tube to a perforated cylinder 7, which makes it possible to determine the volume of biogas collected. Owing to this design of biogas collection and measurement formed during fermentation, it is possible, according to the Mendeleev-Clapeyron law, to determine the mass of biogas collected.

In addition, during the operation of the experimental device, a high-speed digital camera 14 was used, which is connected to a personal computer 15. Owing to its work, the following was investigated:

– a change in the thickness of the active sludge on inert media in the range from 10^{-3} m to $4.8 \cdot 10^{-3}$ m (Table 1) and, accordingly, the change in the width of the channel (3);

– the process of formation of gas bubbles, which was described in [35];

– the flat flow of fluid flows in the channels and its hydrodynamics can be described by the Reynolds criterion (2);

– the hydrodynamic conditions in the bioreactor channels are the same since their geometry and fluid input conditions are preserved. Therefore, the speed of movement of wastewater in the channels can be calculated on the basis of the law of continuity of fluid flows (1).

All these studies, owing to a high-speed digital camera, were taken into consideration when studying the effect of hydrodynamics on the efficiency of the mass transfer process.

Thus, one can draw the following conclusions:

– the volume of biogas released increases with increasing experiment time, and this is shown on the plot of dependences of the collected biogas on the duration of the experiment at different wastewater rates (Fig. 2). This is due to the low concentration of microorganisms in the biofilm at the beginning of bioreactor operation;

– the volume of biogas released increases with an increase in the rate of wastewater in the bioreactor channels due to the movement of the substrate (glucose) from the liquid flow to the laminar boundary layer. It is in this layer that mass transfer occurs due to molecular diffusion, which is mainly carried out due to convective diffusion. This can be seen in the dependence plot of the specific performance of the bioreactor for biogas on the rate of wastewater (Fig. 3);

– the increase in the coefficient of mass yield β_x from the Reynolds criterion (Fig. 4), which characterizes the hydrodynamics of the flow. This dependence can be determined using regression analysis and described by empirical equation (10);

– during the two-dimensional movement of wastewater in the channel, two types of mass transfer occur: convective diffusion in the flow nucleus and molecular diffusion in the borderline flow layer of the biofilm. And it is in the second type of mass transfer where the main diffusion resistance is concentrated.

Ensuring stable and uninterrupted operation of the bioreactor with immobilized microorganisms is limited to maintaining the anaerobic process, enabling a stable temperature, continuous substrate supply [12, 13], and stable growth of the biofilm [24]. The rate of mass transfer through the biofilm can control the overall speed of the substrate degradation process, which in turn depends on the substrate flow regime and the properties of the biofilm. The hydrodynamic situation in the bioreactor affects the formation of the biofilm structure, the contact of microorganisms with the carrier, as well as the physical properties of the biofilm, such as the density and strength of adhesion to the carrier [27, 28].

The experiments were conducted under the following conditions:

– the ambient temperature changed within 16÷20 °C;

– the temperature in the bioreactor was maintained at 35–37 °C;

– the performance of the resulting biogas, depending on the rate of wastewater, was from 0.0011 to 0.11 m^3/h.

The disadvantage of using bioreactors with immobilized microorganisms is to enable the absence of stagnant zones and constant automatic monitoring. In addition, depending on changes in the external air temperature, it is necessary to change the temperature of the incoming substrate to the bioreactor.

The experimental installation developed for practical implementation is easy to use, portable, and effective, by adjusting the substrate feed rate to the bioreactor, thermostat-

ing, and the ability to register the experiment on a personal computer. Owing to the experimental data given in Table 1 and shown in Fig. 2, in the future, it is possible to construct a mathematical model that will take into consideration the influence of hydrodynamics of wastewater on the process of mass transfer in bioreactors. It is also planned to study on carriers of various shapes for the immobilization of active sludge [36] to determine the best mass transfer of the substrate to the biofilm.

7. Conclusions

1. A model structure of a wastewater treatment plant with microorganisms immobilized on inert carriers has been designed. The experiment was conducted under the mesophilic mode to maintain the methane growth of microorganisms. During experimental studies, it was found that the width of the channel in the bioreactor changes due to a change in the thickness of the biofilm in the range from 10^{-3} m to $4.8 \cdot 10^{-3}$ m.

2. It has been established that the hydrodynamic conditions in the bioreactor channels are the same, so the speed of movement of wastewater in the channels can be calculated on the basis of the law of continuity of fluid flows. A criterion equation is derived by which the mass transfer coefficient can be calculated. Owing to it, it is possible to calculate the size of an anaerobic bioreactor and conduct a simulation of the operation of the device to determine its power. It was experimentally recorded that the volume of biogas released increases with an increase in the rate of wastewater in the bioreactor channels due to the fact that the movement of the substrate occurs with the flow of liquid to the laminar boundary layer.

Conflict of interests

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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