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**SUBSTANTIATION OF THE PARAMETERS
OF A THREE-STAGE BIOREACTOR
FOR MANURE DISINFECTION**

Abstract. The paper reviews the energy indicators of a three-stage bioreactor for the technological production of liquid organic fertilizer. The results of the mathematical and theoretical models of the bioreactor are given. The technological parameters of the developed three-stage bioreactor based on the uniqueness of similarity theory methods and thermal similarity criteria are substantiated.

Key words: agriculture, biofertilizer, processing, manure, waste, bioreactor, animal husbandry, fermentation, manure removal.

Introduction. The basis for controlling the biosynthetic activity of microorganisms is the reaction of a microbial cell to a change in external conditions. Therefore, for the development of process conditions in microorganisms cultivation, it is necessary to investigate how the system state affects on the kinetics of methanogenesis. This would allow to obtain initial data for the development of a constructive-technological scheme of high-performance equipment

The physical macroscopic values characterizing the system state are parameters of its state. As parameters of the state of individual elements of the simulated object consider the temperature of the substrate, the intensity of circulation, contributing to the acceleration of the rate of biochemical reactions, increasing the energy content of the substrate, the concentration of hydrogen ions (pH), in the subsequent reduction of the process time.

Geometrical dimensions: length, width, height, diameter, surface area, circulation speed, mixing intensity and volume of bioreactors and gas-holder are the design characteristics of the object under study [9].

The values of the specific growth rate of the crop and the dilution rate of the crop, the intensity of circulation are the consumption characteristics.

Research methodology. All physical quantities used for the mathematical description of the microbiological process are divided into 2 groups - variables and constants. Physical variables include ambient temperature and crop dilution rate, duration of acid and alkaline fermentation stages, circulation intensity and biogas output. Constant physical quantities are the heat capacity, density and viscosity of the substrate.

In biological redox processes, which include methane fermentation, the concentration of hydrogen ions (pH) significantly affects the activity of enzymatic reactions. Many experts believe that the optimal pH value for methane bacteria is 7–7.6, the expansion of this interval to 6.5 reduces the output of biogas by 30–40%, and to 6 - almost completely inhibits the development of methane microflora [1].

Thus, the stability and intensity of the methane digestion process in a bioreactor depends on the balance of all stages of the process, the optimal interaction of all groups of microorganisms in each phase of processing.

A model of a microbiological process can be represented as an equation describing the dilution rate of a crop in a substrate [2]:

$$\frac{dx}{d\tau} = (V_{growth} - V_{dil}) * n_c * q * x, \quad (1)$$

where x – the number of bacteria in 1 ml of the substrate; τ – the time of the process; V_{growth} – the specific growth rate of the crop; V_{dil} – the dilution rate of the crop, depending on the loading dose; n_c – circulation rate; q – the circulation energy.

If $V_{dil} = V_{growth}$, then $\frac{dx}{d\tau} = 0$, that is, the number of bacteria in the substrate remains constant.

Anaerobic fermentation proceeds most efficiently with a constant increase in the number of microorganisms. Thus, the condition for the intensification of the process is:

$$V_{dil} < V_{growth}, \text{ then } \frac{dx}{d\tau} \geq 0. \quad (2)$$

The dependence of the growth rate of the number of microorganisms on the temperature of the medium is described by an empirical formula [56,57]

$$\mu_t = 0,013 \cdot t - 0,129, \text{ day}^{-1}, \quad (3)$$

where t – process temperature, °C.

Then, in the psychrophilic mode ($t=20^\circ\text{C}$) $\mu_t = 0,013 \cdot 20 - 0,129 = 0,13 \text{ day}^{-1}$, in mesophilic mode ($t=30^\circ\text{C}$) $\mu_t = 0,013 \cdot 30 - 0,129 = 0,26 \text{ day}^{-1}$, and in thermophilic mode ($t=55^\circ\text{C}$) $\mu_t = 0,013 \cdot 55 - 0,129 = 0,58 \text{ day}^{-1}$.

Secondly, the growth rate depends on the dilution rate, which depends on the loading dose of the bioreactor [57]

$$D = \frac{Q_{LS} n_c}{Q_{SB}} 100, \quad (4)$$

where Q_{SB} – the mass of the substrate in the bioreactor; Q_{LS} – the mass of the loaded substrate; n_c – circulation rate.

Thus, the analysis of dependencies (2) – (4) allows us to conclude that the growth rate of microorganisms depends on the stage of the fermentation process, the bacterial composition, temperature, loading dose, circulation rate and time of the process.

Analysis of the research shows that to calculate the biogas output, it is advisable to use the Kontokinetic model [8], which takes into account the process temperature, the duration of fermentation (exposure) and the growth rate of microorganisms, then the objective function can be written in the form:

$$B = B_{LIM} S_{OM} n_c \left(1 - \frac{K}{\mu_t \tau - 1 + K}\right) \rightarrow \max, \quad (5)$$

where B – biogas output from 1 m³ of the bioreactor volume, m³/m³; B_{lim} – the limit output of methane per unit mass of the substrate for an infinitely long duration of the process; S_{OM} – concentration of organic matter in the substrate, %; τ – duration of fermentation, days; K – kinetic parameter of the process.

The obtained data are confirmed by the experience of operating biogas plants in Denmark, in which the first stage of digestion takes place in the reactor for primary processing, and then the substrate is pumped into the reservoir for subsequent processing (“cold” reservoir). This technology allows to increase the output of biogas to 4 m³/m³.

Based on the obtained data, an improved technology of accelerated digestion of agricultural biowaste was developed, which was investigated on a laboratory sample of a three-stage bioreactor with a total volume of 0.15 m³.

The efficiency of the facility largely depends on the bioreactor thermal regime. The bioreactor is the main element of the design of biogas plants, where the process of biochemical transformation of animal waste occurs. The main criterion of the fermentation process in the bioreactor is the temperature of the substrate, as well as the intensity of biogas recovery and the processing time of the substrate.

To implement the technological process in biogas plant substrate temperature t_p of three-stage bioreactor is set, then the thermal power Q_{FB} is taken as an unknown quantity, and the temperature t_p is an independent input.

The solution of the problem in this formulation can be carried out within the framework of both the stationary and non-stationary thermal conditions. In the first case, it boils down to determining the P_{FB} rated heat power of the fuel boiler; in the second case, there is the law of temperature variations in the heat transfer media, in the system t_i and the three-stage bioreactor t_p .

Based on the theory of heat exchangers, the following assumptions are made: the temperature of the coolant flow is assumed to be the same throughout the section of pipes, there are no internal heat sources in the coolants, the accumulating capacity of the walls of the heat exchangers can be neglected, the heat capacity of all the elements of the system is characterized by average heat transfer coefficients and heat transfer [4-6].

The heat flows of the bioreactor are shown in the schematic diagram of the heat exchange of its elements (1). Based on the above, the equations of an analytical model of a biogas plant are formed. Solving (5), we obtain a description of the dynamics of heating in individual elements.

The equation of the heating dynamics of the coolant in the fuel boiler HE:

$$t_{iout} = t_{i0} e^{-\tau/T_1} + t_{ist} \left[1 - e^{-\tau/T_1} \right], \quad (6)$$

$$T_1 = \frac{G_i c}{K_{HT} F_{HT}}, \quad (7)$$

where T_1 – time constant; t_{ist} – stable temperature.

Equating the heat transfer HT equations and the change in the enthalpy of biomass in the bioreactor, we determine the temperature t_l''

$$t_l'' = \frac{t_l' - t_n (B+1)}{B}, \quad (8)$$

$$B = e^{\frac{K_{HT} F_{HT}}{G_l c}}, \quad (9)$$

where $t_l'; t_l''$ – initial and final coolant temperature in HT.

Structural model of laboratory installation of three-stage bioreactor: 1 - bioreactor; 2 - heating element (HE); 3 - container for substrate preparation (CS); 4 - blade of substrate mixer; 5 - thermal isolation; 6 - electric pump-substrate shredder (LV); 7 - process pipelines (PP); 8 - mixer; 9 - valve for gas; 10 - container for accumulation of finished fertilizer (CF)

Based on the above, the equations of an analytical model of a biogas plant are formed:

$$\left. \begin{aligned}
 P_{FB} d\tau &= G_i c d t_i + K_{HT} F_{HT} (t_i - t_n) d\tau - G_q c (t_{inq} - t_{outq}) d\tau \\
 K_{HT} F_{HT} (t_i - t_n) d\tau + K_{TV} F_{TV} (t_q - t_n) d\tau &= \\
 &= G_{BP} c d t_n + M_b c_c d t_n + K_{BP} F_{BP} (t_n - t_0) d\tau \\
 C_l \frac{d t_l}{d \tau} + K_{HT} F_{HT} (t_i - t_n) &= G_l c (t_{inl} - t_{outl}) \\
 C_q \frac{d t_q}{d \tau} + K_{TV} F_{TV} (t_q - t_n) &= G_q c (t_{inq} - t_{outq}) \\
 t_i &= \frac{t_{\text{exlxi}} + t_{\text{exi}}}{2}; \quad p = i, l, n, q; \quad t_p(\tau = 0) = t_{pH}
 \end{aligned} \right\} \quad (10)$$

where P_{FB} – heat power of the fuel boiler; t_{in}, t_{out} – temperatures of coolant at the inlet and outlet of the corresponding elements; t_a – ambient temperature; t_i, t_l, t_q, t_n – the temperature of the coolants in the FB, HT, TP, biogas plant; K_{HT}, K_{TV} – heat transfer coefficients of HT and TP; K_{BP} – coefficient to the heat transfer to the environment in a biogas plant; F_{HT}, F_{TP} – according to the heat transfer surface HT, TP; F_{BP} – surface heat transfer to the environment to the biogas plant; G_i, G_l, G_q – respectively the costs of coolants in the FB, HT, TP; τ – time, c_B, c_c – respectively, specific heat capacities of water, biomass ($C_B = 4.06 \text{ kJ/kg}^\circ\text{C}$) and steel; G_{BP}, M_B – the mass of the substrate and the body of a biogas plant; C_l, C_q – full heat capacity of the corresponding elements.

Solving (6), we obtain a description of the dynamics of heating in individual elements.

The equation of the heating dynamics of the coolant in the fuel boiler FB.

The time of heating the biomass up to a given temperature t_n'' is equal [7, 8].

$$\tau_{BP} = T_2 \ln \frac{t_n'' - t_l' \left[\frac{(B-1)}{(B+1)} \right]}{t_n' - t_l' \left[\frac{(B-1)}{(B+1)} \right]}, \quad (11)$$

$$T_2 = \frac{B(G_{BP} c_B + M_b c_c + Q_{OC})}{G_l c(B+1)}, \quad (12)$$

where t_n', t_n'' – biomass temperature at the beginning and end of heating; T_2 – constant time of bioreactor in biogas plant; Q_{OC} – specific heat loss.

Thermal power of the heating element (HE) required heating the bioreactor [67]

$$P_{FB}^1 = \frac{(C_{BM} G_2 + C_{BG} G_3 + C_s M_b) \cdot (t_p^{11} - t_p^1)}{\eta_1 \eta_{HT} \tau_p}, \text{ kJ}, \quad (13)$$

where G_2 – biomass amount, kg; C_{BG} – specific heat capacity of biogas, $C_{BG} = 2.34$ kJ/kg; C_s – specific heat capacity of the steel of body, $C_s = 0.46$ kJ/kg; M_b – mass of the body, kg; G_3 – the mass of biogas in the gasholder; $G_{BG} = V_p$, kg; V – the volume of a gasholder, m^3 ; ρ – the biogas density, normal, $\rho = 1.2$ g/l; τ_p – the heating time of the biomass in the bioreactor, h; η_{HT} – the efficiency of the heat transfer, $\eta_{HT} = 0.92$; t'_p ; t''_p – the initial and final temperature of the biomass in the bioreactor, °C.

The initial and final temperatures of the biomass in the reactors, respectively, $t'_2 = 20^\circ\text{C}$; $t''_2 = 49^\circ\text{C}$, $t''_3 = 69^\circ\text{C}$, inlet and outlet of the heat transfer $t'_2 = 30^\circ\text{C}$; $t''_2 = 69^\circ\text{C}$, $t''_3 = 89^\circ\text{C}$.

Analysis of the obtained data indicates that the heating time of the biomass, taking into account the intensity of circulation in three-stage bioreactors to a thermophilic temperature of 80°C is 120 h, the installed total thermal power of the HE is 5.9 kW.

To substantiate the technological parameters because of the complexity of the description of physical quantities, we use the dependencies between the similarity criteria and the “criterion equations”. For the conditions of forced flow of a thick fluid in pipelines for circulation, mixing and heat transfer by the method of the theory of similarity in the general case to functional relationships through the Nusselt criterion [6; 7; 8]

$$Nu = f.(Re, Gr, Pr, l/d), \quad (14)$$

where l/d – the ratio of the length of the pipe to its diameter, which takes into account the change in heat transfer along the length of the pipe, associated with hydrodynamic and heat flow stabilization in the initial section, $Re = \omega d / \nu$ – Reynolds criterion, $Gr = gl^2 \beta \Delta T / \nu$ – the Grashof criterion, $Pr = gl / \omega^2$ – the Froude criterion.

To calculate the parameters of pipelines and injection pump in the system, we determine the volume (flow) of fluid Q_f :

$$Q_f = \omega * C \sqrt{R * J}, m^3/h, \quad (15)$$

where C – the Chézy coefficient, $J = h/l$ is the hydraulic slope, ω – the area of the living section, R – the hydraulic radius, d – the pipe diameter (m).

Power consumption of the injection pump:

$$N_n = \rho * g * Q_f * P, kW, \quad (16)$$

where N_n – the net power; $\rho = kg/m^3$ density of the pumped area; H – total pressure in m.

Power on the pump shaft N_s :

$$N_s = N_n / \eta_p, kW, \quad (17)$$

where $\eta_p = 0.96$ pump efficiency;

Engine power consumption N_e :

$$N_e = N_s / (\eta_p * \eta_e), kW, \quad (19)$$

where $\eta_d = 0.98$ drive efficiency; and $\eta_e = 0.95$ engine efficiency;

Installed power N_{inst} :

$$N_{inst} = \beta * N_e, kW, \quad (20)$$

where $\beta = 1.6$ coefficient of power reserve up to 1 kW (2–1.5).

Research results and discussion. The basis for controlling the biosynthetic activity of microorganisms is the reaction of a microbial cell to a change in external conditions. Therefore, for the development of technological regimes of microorganisms cultivation, it is necessary to investigate how the state of the system affects the kinetics of methanogenesis. This will allow to obtain initial data for the development of a constructive-technological scheme of high-performance equipment.

To calculate the energy indices, the substrate temperature of the three-stage bioreactor is set, which is necessary to implement the technological process, then the total energy consumption for maintaining the Q_{SUMM} process is taken as an unknown quantity, and the temperature t_p is an independent input.

The technology of controlled three-stage anaerobic digestion and thermal neutralization allows to reduce costs, and the complex of automatic control and management minimizes the involvement of personnel and allows obtaining a stable quality of liquid fertilizers [5].

A pump carries out submission of the substrate to the first reactor, where the process of fermentation begins, of anaerobic fermentation at temperatures up to 50°C. To the second reactor, the substrate is pumped from the first reactor with temperature ($t_{p1} = 46^\circ\text{C}$), where the fermentation process continues, anaerobic fermentation with a higher temperature - about 70°C, which results in accelerated decomposition of organic waste.

The substrate is pumped to the third reactor from the second reactor with a temperature ($t_{p2} = 66^\circ\text{C}$), where it continues, where the process of high-temperature treatment takes place with a temperature ($t_{p3} = 96^\circ\text{C}$), which results in an accelerated neutralization of organic waste. The substrate in the bioreactors is mixed automatically to a homogenous consistency during 15 minutes, every 4 hours.

The solution of the problem in this formulation can be carried out within the framework of both the stationary and non-stationary thermal conditions. In the first case, it boils down to determine the estimated total energy consumption Q_{SUMM} to maintain the process, the second is the law of the time variation of the loading temperature $t_{\text{load}1}$, $t_{\text{load}2}$, $t_{\text{load}3}$ and the temperature in the three-step bioreactor t_{p1} , t_{p2} , t_{p3} . Based on the above, the equations of an analytical model of a biogas plant are formed.

Conclusions. The analysis results on indicators of the processes in the thermo-biological processing of the substrate in a three-step bioreactor due to the continuity of the processing stage of the substrate proves the acceleration of the anaerobic fermentation process by 3 times. The use of a three-step bioreactor allows to organize the continuous production of liquid organic fertilizers with high energy efficiency.

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КӨНДІ ЗАЛАЛСЫЗДАНДЫРУҒА АРНАЛҒАН ҮШСАТЫЛЫ БИОРЕАКТОРДЫҢ ПАРАМЕТРЛЕРІН НЕГІЗДЕУ

Аннотация. Мақалада сұйық органикалық тыңайтқыштың технологиялық өндірісі үшін үшсатылы биореактордың энергетикалық өнімділігі қарастырылады. Биореактордың математикалық және теориялық модельдерінің нәтижелері келтірілген. Ұқсастық теориясы әдістеріне және термиялық ұқсастық критерийлерінің бірегейлігіне негізделген үшсатылы биореактордың технологиялық параметрлері негізделген

Түйін сөздер: ауылшаруашылығы, биотыңайтқыштар, қайтаөңдеу, көң, қалдық, биореактор, малшаруашылығы, ашыту, көнді жинау.

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ОБОСНОВАНИЯ ПАРАМЕТРОВ ТРЕХСТУПЕНЧАТОГО БИОРЕАКТОРА ДЛЯ ОБЕЗЗАРАЖИВАНИЕ НАВОЗА

Аннотация. В статье рассмотрены энергетические показатели трехступенчатого биореактора для технологического производства жидкого органического удобрения. Приведены результаты математического и теоретического модели биореактора. Обоснованы технологические параметры разработанного трехступенчатого биореактора на основе условий однозначности методов теории подобия и критериям теплового подобия.

Ключевые слова: сельское хозяйства, биоудобрение, переработка, навоз, отход, биореактор, животноводства, сбраживания, уборка навоза.

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