Modeling of heat exchange processes in the Metanetka bioenergy plant for individual use

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Abstract: A bioenergy plant with a solar heating system for individual use has been developed and built, intended for the processing and disposal of agricultural waste of organic origin to obtain biogas and liquid high-quality organic fertilizers under conditions of anaerobic fermentation. The main features of heat transfer processes in bioreactors are considered. A mathematical model is proposed that describes these processes. The use of the resulting model will improve the control processes of reactors and comply with technological regimes.

1. Introduction

Currently, economically developed and developing countries are rapidly developing on the practical use of alternative energy sources as an important factor in sustainable development and increasing the competitiveness of economies in the face of a decrease in global reserves of hydrocarbons. Biomass is one of the most common alternative energy sources. Technologies for processing biological raw materials have found wide application for solving the problem of environmentally safe disposal of organic waste, reducing environmental pollution, as well as obtaining alternative energy, biogas and valuable biofertilizers. Denmark, Germany, USA, China, India and other countries are the leaders in this production. In the total energy balance of Denmark, biogas takes 18%, Germany - 8%, however, the latter is the leader in the number of medium and large biogas plants 10,000 pcs. By 2020, the EU forecasts biogas production in the amount equivalent to 29.43 million toe, which is equivalent to 36.29 billion m3 of natural gas [1-5].

Uzbekistan has accumulated considerable experience in conducting scientific and experimental research in the field of using alternative energy sources, primarily solar and biogas energy, for which development has been carried out for many decades. According to the strategy of innovative development of the Republic of Uzbekistan, by 2025 it is planned to increase the share of electricity production using renewable and alternative energy sources by more than 25%, and one of the main directions in the implementation of this task is the development of energy alternative and renewable resources [2, 5-7].

2. Research Methodology

Today, there are various methods for assessing the work of pilot and industrial plants for biogas production, a set of their principles, methods and processes, as well as means of their
implementation. Many authors noted that various factors affect the biogas production process, such as the potential of the feedstock, the design of the biogas plant, the physical and mechanical properties of the loaded organic waste, the frequency of loading, internal and external mechanisms for maintaining temperature and humidity, etc. But besides this, it is necessary to note the importance of the human factor in the correct operation of the process of producing biogas and organic fertilizers.

The correct operation of the biogas plant equipment, as well as the diagnosis of failures in its operation, depends on the knowledge of the microbiological sequence of the anaerobic process and the experience of the operator. The basis of traditional methods for evaluating and analyzing equipment is the presence of an unambiguous functional relationship of the analyzed features with the parameters of the technical state of the biogas plant being evaluated, which limits their use only for technically simple units and mechanisms. Currently, a large number of plants for the production of biogas from organic waste in various countries have been developed and are operating. However, most scientifically grounded biogas plants are intended for processing waste from large livestock breeding complexes and provide for heating the fermented biomass using electricity or heat from centralized networks, which hinders the effective disposal of waste from individual and small farms dispersed in regions with no centralized power supply [6, 7].

2.1. Solutions

The change in the structure of agricultural production in connection with the transition to market conditions led to an increase in the number of private dekhkans and farms. When solving the issues of energy supply for everyday life, individual and farms in remote areas of Uzbekistan, which do not have centralized electricity and gas supply, feel the need for imported fuel materials [8, 9].

Therefore, the development of small bioenergy plants (BEU) with heating of the fermented biomass at the expense of local renewable energy sources is an urgent problem, the solution of which contributes to the direction of effective waste disposal while ensuring environmental safety in agricultural production in remote regions.

All this dictates that for large-scale use of biogas plants in farms and individual agriculture, first of all, given their regional and local conditions, the need to develop small energy-saving, economical, environmentally friendly and high-performance ECUs.

In this regard, an experimental bioenergy installation of a production nature with a solar heating system, intended for individual use, was built at the Bukh.IIT capabilities, intended for individual use, consisting of a bioreactor, a solar collector, a heat accumulator, a gas purifier and a gas storage tank (gasholder). Research on obtaining biogas and high-quality biofertilizer are given in [4].

However, when describing the MT designs (digester-bioreactor) and the biomass fermentation technology, they do not touch upon the issues of their analytical description, as well as the process of heat exchange in MT and with the environment. Since the process of heating the substrate depends on many factors: the thermal resistance of the reactor walls, the type and mass of the substrate, its thermophysical properties, and the temperature of the coolants, the size and design of heat exchangers, the mode of mixing the substrate [10-26].

This work is devoted to the development of mathematical models of the heat transfer processes occurring during the fermentation of the substrate in biogas reactors.

3. Results and Discussion

For the analysis of heat transfer processes, consider a cylindrical biogas reactor. To maintain the temperature in the reactor, a heat exchanger in the form of pipes spirally wound from the inside of the reactor is used as a heater, through which a hot coolant (water) circulates. To minimize heat loss to the environment, the reactor is covered with an insulation layer. The reactor is also equipped with a paddle stirrer Figure 1.

The temperature of the medium in the biogas reactor is a function of time $T_1 = f(\tau)$.

Let us take constant the temperature of the coolant at the supply $t_1^1$, which transfers the substrate heat $Q_2$, the thermal resistance of the reactor wall $R$, the area of the heat exchange surface of the heater (heat
exchanger) F_2, the area of the reactor side surface F_1 over which heat loss Q_1 occurs to the environment, the volume of the reactor W.

Figure 1. Biogas reactor with paddle stirrer and heat exchanger 1., 5- loading and unloading hatches; 2-blade stirrer; 3- biogas discharge pipeline; 4-insulated body; 5-return coolant pipeline; 6-coolant supply pipeline

Variable quantities are the water temperature \( t_{2_1} \) at the outlet of the heat exchanger-heater; the coefficient of heat transfer from the heater to the fermentable biomass \( K_2 \), depends on the thermophysical properties of the substrate and heat carrier, the mode of washing the heat exchange surface; outside temperature \( t_{out} \). The differential equation for the heat balance of the reactor under non-stationary operating conditions is written in the form:

\[
W \cdot \rho \cdot c_1 \frac{d t_1}{d \tau} = G_2 \cdot G_2 (t_{1_1} - t_{2_1}) - \frac{F_2}{R} \cdot (t_1 - t_{out})
\]  
(1)

where \( \rho \) is the density of the substrate; \( c_2 \) - heat capacity of the heat carrier; \( c_1 \) - heat capacity of the substrate. Thermal properties of the substrate will be found according to the equations given in [6, 7 and 8]:

\[
\rho = 1000 + 2 A \cdot c
\]  
(2)

\[
c_1 = c_{dry} \cdot s + c_{w} \cdot (1 - s)
\]  
(3)

\[
\mu = \mu_0 \cdot [1 + 10^{(c - 2) \left(11 - \beta_u \mu c^c \right)} + c]
\]  
(4)

Where \( s \) - dry matter content 2 ... 15%;
\( C_{dry} \) - heat capacity of substrate dry matter; \( C_{w} \) - heat capacity of water; \( \mu_0 \) - viscosity of water at a specific temperature; \( \beta_u \) - coefficient, depending on the type of effluent and is 0.7 ... 0.75 for cattle.

Due to the nonstationarity of the process, the return water temperature is also variable \( t_{2_1} \), the value of which is found from the heat balance of the heat exchanger:

\[
dQ = G_2 \cdot c_2 (t_{1_1} - t_{2_1}) d\tau = F_2 \cdot K_2 \cdot \Delta t \cdot d\tau
\]  
(5)
We find the average temperature head in the heat exchanger according to the well-known formula

\[ \Delta t_c = \frac{\Delta t_a - \Delta t_i}{\ln \frac{\Delta t_a}{\Delta t_i}} \]  

(6)

where \( \Delta t_a = t_1 - t_1^1 \), \( \Delta t_i = t_1 - t_2^1 \)

Substituting the values of the average temperature difference \( \Delta t_c \) into equation (5), we determine that the temperature of the return water from the heat exchanger

\[ t_2^1 = \frac{R_2^2 \cdot P_2}{R_2^1 \cdot P_2} \left( \frac{\Delta t_2}{\ln \frac{\Delta t_2}{\Delta t_1}} + t_1^1 \right) \]  

(7)

The value of the heat transfer coefficient \( k_2 \) is found using empirical equations for the coefficient of heat transfer from the coolant to the wall of the heat exchanger-heater [9]:

\[ N u_1 = 0.021 R e_1^{0.8} \cdot P r_1^{0.43} \left( \frac{P r_1}{P r_2} \right)^{0.25} \]  

(8)

To determine the coefficient of heat transfer from the heater wall to the substrate when the heater is washed with a stirrer at the maximum technological speed, we will use the empirical dependence given in [9] for the transverse washing of a single pipe in the range \( 1000 \leq R e \leq 20000 \),

\[ N u_2 = 0.25 \cdot R e_2^{0.6} \cdot P r_2^{0.38} \left( \frac{P r_1}{P r_2} \right)^{0.25} \]  

(9)

where \( R e_1 \) is the Reynolds criterion for the flow of the coolant in the pipe; 
\( R e_2 \) - Reynolds criterion when washing the heater with the substrate; 
\( P r_1 \) - Prandtl criterion for the heat carrier at its average temperature 
\( P r_2 \) - Prandtl criterion for the substrate at its average temperature 
\( P r_3 \) - the same, the same at the wall temperature.

Modeling in the mathematical package MathCad is carried out in accordance with the initial conditions: coolant temperature \( t_1^1 = 40 ^\circ C \); thermal resistance of the wall of the insulated reactor \( R = 1 \text{ m}^2 \text{°C/W} \); side surface area of the reactor \( F_1 = 8 \text{ m}^2 \); coolant flow rate \( G_2 = 0.1 \text{ m}^3/h \); heat transfer area of the heater-heat exchanger \( F_2 = 3 \text{ m}^2 \); reactor volume \( W = 3.5 \text{ m}^3 \) (the volume of the substrate is taken \( W' = 2.5 \text{ m}^3 \)); external temperature \( t_{out} = 15 \text{ °C} \); dry organic matter content \( s = 8\% \), cattle waste \( \beta_u = 0.7 \)

Nominal diameter of the heater pipe 25 mm Based on the results of numerical simulation, a graphical dependence of the heating time of the substrate in the reactor on the process temperature was obtained (Figure 2).
When developing a mathematical model, it is assumed that the temperature of the substrate is uniform throughout the volume. Uniform heating of the substrate in the bioreactor can be achieved only with thorough mixing within the technological speed. When examining the return water temperature, special attention should be paid to the operating temperature difference \((t_1^1 - t_2^1)\), which for the normal functioning of the bioreactor should be within 5 ... 8 °C.

If you use a poorly insulated or non-insulated bioreactor \((R = 0.04 \text{ m}^2 \cdot \text{oC/W})\) and with an incorrectly selected heat exchanger \(F_2 = 0.2 \text{ m}^2\), then some required temperature conditions cannot be achieved at all, the nature of the \(\tau\) dependence is an unattainable mesophilic regime in improperly designed bioreactor. This happens because with an increase in the heating time of the substrate in the most insulated bioreactor, the temperature of the anaerobic process practically does not reach the optimal value to maintain the maximum productivity of biogas production.

![Graph](image)

**Figure 3.** Dependence of heating time of non-insulated bioreactor on process temperature

In subsequent years, scientists who studied mixed or pure cultures of bacteria in organic waste involved in the process of methane fermentation continued to give them systematic names, adhering to the previous principle. The peculiarities of microorganisms, consisting in the uniformity of a set of external and internal signs acquired as a result of individual development in individual sections of the bioreactor, the lack of available methods for identifying the set of genes of a given methane-forming bacteria really do not allow using other approaches to classification and nomenclature that carry out the process of methane fermentation under changing temperature conditions. That is why the study of methane-forming bacteria revealed the need for a comprehensive comparative assessment of their biochemical characteristics and their comparison with the characteristics of already known microorganisms. In this case, taking into account the temperature regime of fermentation in any case should be considered as unsteady [27, 28].

### 4. Conclusion

The above equations for determining the thermophysical properties of the substrate allow one to take into account the possibilities of the anaerobic operation of methane-forming bacteria. The proposed mathematical model describing these processes allows us to conclude that the use of the resulting model will improve the control processes of reactors and comply with the technological regimes of the requirements of the anaerobic process. Modeling in accordance with the given initial conditions made it possible to determine that the heating of an insulated reactor with a volume of 3.5 m³ to the mesophilic fermentation mode will take place in 67 minutes, and the thermophilic mode will reach in 2 hours.

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