Mathematical model of heat transfer in the reactor of a biogas plant

A G Fiapshev, M M Khamokov and O Kh Kilchukova
Kabardino-Balkarian state agricultural university named after V.M. Kokov, Nalchik, Russia

E-mail: energo.kbr@rambler.ru

Abstract. The use of technical means for the production of biomethane, as a source of alternative energy, is mainly characterized by design and technological parameters, as well as operating modes of biogas plants. This study was carried out in order to obtain data on the main parameters of a biogas plant and the effect of a heat exchanger-mixer on performance indicators. The convenience of performing mathematical modeling is that it is expensive to carry out experiments on real objects, just as conducting experiments on a real installation is associated with high material costs, as well as high time costs, due to the high inertia of heat exchange processes, and the significant overall dimensions of the biogas plant. The results of mathematical modeling of thermal processes occurring in a biogas plant are presented. The data on the influence of the main parameters of the biogas plant and the heat exchanger-mixer on the quality indicators of its operation were obtained. It is shown that the theoretical temperature homogeneity of the mixed medium is achieved by combining the heat exchanger and the mixing device into one unit, the design and technological parameters characterizing the intensity of the forced movement of the fermented mass, with a change in thermal conductivity.

1. Introduction

Energy studies show that the potential energy reserves lurking in organic waste from world agriculture are estimated at hundreds of billions of kilowatt-hours. So, world agriculture has an area of about a billion hectares, on which the green mass of stems is more than a billion tons of dry matter [1,2], which in terms of calorific value is equal to the same amount of coal, and that part of the chemical energy that is spent on technological losses of this mineralization mass during decomposition in stacks, calculated in terms of electricity, about 2000 billion kWh per year [3]. These energy resources, referred to as "bioenergy resources", significantly exceed the world reserves of hydro and wind energy resources of local importance [4, 5].

It is quite obvious that solving the problem of practical development of potential energy of at least part of bioenergy resources would be of great importance for the development of rural energy, especially if we take into account that their energy is constantly renewable and can be obtained in places of its consumption, being a by-product of the technology of the agrotechnical process preparation of organic fertilizers [6].

An acute problem in the development of the entire agro-industrial complex is the problem of its efficient energy supply [7, 8]. Much attention is constantly paid to traditional energy sources, and until now, they have been rather wary of the use of non-traditional energy sources [9-11]. One of the promising areas for processing poultry and livestock waste is anaerobic digestion, which allows biogas...
to be obtained, and organic fertilizer from the fermented mass. At the same time, environmental pollution is significantly reduced [12].

To intensify the fermentation process and optimize the design and energy parameters of the digester, it is proposed to combine a mixing device (mixer) and a heating element into one unit, i.e. the stirring device is also a heating element. This combination allows you to heat and maintain a given temperature regime more evenly due to the rotation of the heat exchanger and the transfer of heat to the biomass (substrate) throughout the digester volume, since the temperature uniformity in the moving medium is directly related to the phenomena occurring in the thermal boundary layer, in contrast to all existing ones. heat exchangers (water jacket, tubular stationary) which allow heating only limited areas, which leads to uneven heating.

The release of biomethane is intensified by adding green mass processing waste to the manure, and in the case of processing waste with a high content of straw, cattle manure. With the presence in one complex of lines for fractionation of green mass, chemical treatment of straw and a bioenergy plant, it is possible to ensure the production of a dry protein concentrate suitable for long-term storage. With the complex bioconversion of plant raw materials, biomethane can be rationally used throughout the year in summer for processing green mass, in winter for thermochemical treatment and in heating installations.

2. Materials and methods

Research and analysis of thermal processes of the developed installation were carried out using mathematical modeling, which can be described by equations of thermodynamics.

3. Research results

Biomethane can serve as a heat source for a biogas plant. In addition, the heat from the fermented mass can be used to preheat the feed liquid manure (using a surface heat exchanger).

Consideration of the process of forming a mathematical model of a part of a bioreactor (Figure 1) facilitates the study of thermal processes occurring in this installation [13].

To describe the mathematical model, we take the basic notation: $x, r$ – spatial coordinates (Figure 2); $\tau$ – time; $R(\alpha), \alpha=1,2,...,8$, $\Delta R_M, \Delta R_R$ – geometric dimensions of the bioreactor along the axis $r$; $X(\alpha), \alpha=1,2,...,5$, $\Delta X_M$ – geometric dimensions of the bioreactor along the axis (Figures 3,4).

Figure 1. Geometrical parameters of the bioreactor and heat exchanger-mixer.

Figure 2. Simplified diagram of a part of a bioreactor.
The system of heat conduction equations for the object under consideration can be represented as:

$$\frac{\partial T}{\partial \tau} = a(\beta)\nabla^2 T; T = f(x, r, \tau), \beta = 1, 2, \ldots, 4;$$

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{1}{r} \frac{\partial}{\partial r} + \frac{\partial^2}{\partial r^2}, \tau > 0.$$ 

To solve the resulting system of partial differential equations, we describe the boundary and boundary conditions.

We write the boundary conditions in the form of the following system of equations.

Due to the fact that the outer part of the chamber is thermally insulated, we get:

$$\frac{\partial T(x, r, \tau)}{\partial r} = 0; 0 \leq x \leq X(5); r = R(8) + \Delta R_g; \tau \geq 0.$$ 

In accordance with the symmetry condition, the following condition is fulfilled in the center of the camera:

$$\frac{\partial T(x, r, \tau)}{\partial r} = 0; 0 \leq x \leq X(5); \tau \geq 0.$$ 

Above and below, in accordance with the characteristics of the bioreactor, the following conditions are accepted:

$$\lambda(1) \frac{\partial T(x, r, \tau)}{\partial x} = q_1(\tau), x = X(5); 0 \leq r \leq R(1); \tau \geq 0;$$

$$-\lambda(1) \frac{\partial T(x, r, \tau)}{\partial x} = q_2(\tau), x = X(5); R(1) < r \leq R(8) + \Delta R_g; \tau \geq 0;$$

$$-\lambda(1) \frac{\partial T(x, r, \tau)}{\partial x} = q_3(\tau), x = 0; 0 \leq r \leq R(8) + \Delta R_g; \tau \geq 0.$$ 

Next, we write the conditions at interfaces ($\tau \geq 0$):

From
\[ S5: \lambda(2) \frac{\partial T(x,r,\tau)}{\partial r} = \lambda(3) \frac{\partial T(x,r,\tau)}{\partial r}; 0 \leq x \leq X(\tau) + \Delta X_m; r = R(\tau) \]

to

\[ S37: \lambda(4) \frac{\partial T(x,r,\tau)}{\partial r} = \lambda(4) \frac{\partial T(x,r,\tau)}{\partial r}; 0 \leq x \leq X(\tau) + \Delta X_m; r = R(\tau) \]

where \( \Delta R_m \) – bioreactor wall thickness; \( \Delta X_m \) – wall thickness of the pipes of the heat exchanger-mixer blades; \( q_1(\tau) \) – heat flow of the heat carrier in the heat exchanger-mixer; \( q_2(\tau), q_3(\tau) \) – heat losses.

The modeling was carried out taking into account the initial conditions that at the initial moment of time the temperature is uniformly distributed over the chamber, i.e. \( T(x,r,0) = T_0 = \text{const} \).

Thermal diffusivity coefficients \( \alpha(\beta) \) materials and substances are determined from the following ratio (m\(^2\)/s):

\[ \alpha(\beta) = \frac{\lambda(\beta)}{\rho(\beta) c(\beta)}, \beta = 1,2,\ldots,4, \]

where \( \rho \) – density of matter, kg/m\(^3\); \( \lambda \) – thermal conductivity coefficient of a substance, W/(m·deg); \( c \) – heat capacity coefficient of a substance, J/(kg·deg).

The heat lost by the bioreactor to the environment is determined by the expression (kJ):

\[ Q_e = M_c(t_b - t_e), \]

where \( M_c \) – weight of the loaded substrate, kg; \( C \) – average specific heat capacity of the substrate, kJ/(kg·ºC); \( t_b \) – initial temperature of the fermentation substrate, ºC; \( t_e \) – initial temperature of the loaded substrate, ºC.

The heat lost by the bioreactor to the environment is determined by the expression (kJ):

\[ Q_p = kF(t_e - t_r), \]

where \( k \) – heat transfer coefficient, kJ/(m\(^2\)·h·ºC); \( F \) – total surface area of the bioreactor, m\(^2\); \( t_e \) – temperature of the mass in the bioreactor, ºC; \( t_r \) – ambient temperature, ºC.

\[ k = 1 \left[ \frac{1}{\alpha_1} + \frac{\sum_{i=1}^{n} \delta_i / \lambda_i}{\alpha_1 + 1 / \alpha_2} \right], \]

\[ k = \frac{1}{1 + \sum_{i=1}^{n} \frac{\delta_i / \lambda_i}{\alpha_1 + 1 / \alpha_2}}. \]
where \( \frac{1}{\alpha_1} \) – thermal resistance of heat transfer from biomass to bioreactor walls; \( \sum_{i=1}^{n} \frac{\delta_i}{\lambda_i} \) – total thermal resistance to thermal conductivity of the bioreactor wall material \( (\frac{\delta_i}{\lambda_i}) \) and thermal insulation material \( (\frac{\delta_i}{\lambda_i}) \); \( \frac{1}{\alpha_2} \) – thermal resistance of heat transfer from the outer surface of the bioreactor thermal insulation material to the ambient air.

The bioreactor must have sealed corrosion-resistant walls, reliable thermal insulation, and reliable loading and unloading devices. The most common reactor shape is cylindrical.

In the future, it is possible to regulate the output of biomethane, for example, by changing the degree of filling of the biogas plant or using special technical devices for mixing.

Therefore, given the technical capabilities, the use of waste as an energy resource is of great importance for agriculture, especially since this energy is renewable and can be produced in places of its consumption as a by-product of the technological process of decomposition and mineralization of organic substances.

Thus, the use of the anaerobic gasification process in agriculture, as a means of integrated use of organic waste, is a new problem that is in an active stage of development, which is of an experimental and research nature in the field of creating technically acceptable and economically viable designs for both bioreactors and energy and technical units of the installation. As evidenced by research results, interest in this problem in scientific circles and among agricultural workers is constantly growing, and the method of using organic waste is becoming more widespread.

There is no doubt that, given the technical capabilities, the use of waste as energy resources would be of great importance for agriculture, especially since this energy is renewable and can be produced in places of its consumption as a by-product of the technological process of decay and mineralization of organic substances.

4. Conclusion

The theoretical temperature uniformity of the stirred medium is achieved by combining the heat exchanger and the stirring device into one unit, which allows heating and maintaining the set temperature regime more evenly throughout the bioreactor volume.

The design and technological parameters of the biogas plant differ from the known ones in that the mixing device and the heating element are combined into one unit. This combination allows heating and maintaining a given temperature regime more evenly due to the rotation of the heat exchanger and the transfer of heat to the biomass (substrate) throughout the digester volume.

Theoretical studies made it possible to obtain a mathematical model of the distribution of the biomass temperature throughout the digester volume.

The results of the study indicate that the main influence on the heat transfer process is exerted by thermal conductivity, density, design and technical parameters of the heat exchanger-mixer.

References

[1] Bondarenko AM and Kachanova L S 2019 Efficiency of technologization of the processing of organic waste of animal husbandry in the agro-industrial complex Economics, management 7 54-61

[2] Baragunov A B, Savvateeva I A, Kushaev S H, Kumakhov A A and Kudaev Z R 2020 Innovative livestock production technology IOP Conference Series: Earth and Environmental Science 32012

[3] Savvateeva I A and Druzhanova V P 2020 Electricity from biogas Topical issues of agricultural science 34 27-37

[4] Tamakhina A Y, Dzakhmisheva I Sh, Beslaneev E V and Gadieva A A 2018 Bioaccumulation of Heavy Metals by Medicinal Plants of the Inula Genus Journal of Pharmaceutical Sciences and Research 10(5) 1263-6
[5] Bondarenko A M and Kachanova L S 2017 Production of liquid concentrated organic fertilizers *Rural mechanic* **11** 30-1

[6] Druzyanova V P, Petrova S A, Okhlopkova M K, Spiridonova A V and Bondarenko A M 2017 Approbation of a new biogas technology: experiments and results *Journal of Industrial Pollution Control* **33**(1) 1058-66

[7] Apazhev A K, Shekikhachev Y A, Fiapshev A G and Hazhmetov L M 2019 Energy efficiency of improvement of agriculture optimization technology and machine complex optimization *E3S Web of Conferences* **124** DOI: https://doi.org/10.1051/e3sconf/201912405054

[8] Apazhev A K, Shekikhachev Y A, Hazhmetov L M, Fiaphev A G, Shekikhacheva L Z, Hapov Y S, Hazhmetova Z L and Gabachiyev D T 2019 Scientific justification of power efficiency of technological process of crushing of forages *Journal of Physics: Conference Series* **1399** 055002 DOI: 10.1088/1742-6596/1399/5/055002

[9] Apazhev A K, Shekikhachev Y A, Batyrov V I, Balkarov R A, Kardanov Kh B, Gubzhokov Kh L and Bolotokov A L 2019 Vegetal fuel as environmentally safe alternative energy source for Diesel engines *IOP Conference Series: Materials Science and Engineering* **663**(1) DOI: 10.1088/1757-899X/663/1/012049

[10] Shekihachev Yu A, Batyrov V I and Shekikhacheva L Z 2019 Use of biofuel as an alternative source of energy in agriculture *Izvestiya of the Kabardino-Balkarian State Agrarian University named after V.M. Kokova* **2**(24) 100-5

[11] Shekihachev Yu A, Batyrov VI, Bolotokov AL and Shekikhacheva L Z 2019 Optimization of the composition of the biofuel mixture *Izvestiya of the Kabardino-Balkarian State Agrarian University named after V.M. Kokova* **3**(25) 90-6

[12] Apazhev A K, Shekikhachev Y A, Fiapshev A G, Kilchukova O Kh and Khamokov M M 2019 Thermal Processes in a Biogas Plant for the Disposal of Agricultural Waste *KnE Life Sciences* 40-50 DOI 10.18502/kls.v4i14.5578

[13] Fiapshev A G, Kilchukova O Kh, Shekikhachev Y A, Khamokov M M and Khazhmetov L M 2018 Mathematical model of thermal processes in a biogas plant *MATEC Web of Conferences* **212** DOI: 10.1051/matecconf/20182120103