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Thermal Processes in a Biogas Plant for the Disposal of Agricultural Waste

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Abstract

The article discusses the thermal processes occurring in a biogas plant in which the mixing device and the heating element are combined into one node, which allows to heat and maintain a given temperature regime more evenly due to the rotation of the heat exchanger and heat transfer to the biomass throughout the entire bioreactor. Required to operate the unit in a thermophilic mode, after its withdrawal to the working state, the heat output is determined by the heat loss of the plant itself and flow with increasing litter temperature to the temperature of the thermophilic mode, which can be described by thermodynamic equations. As a result of theoretical studies, factors have been identified that allow determining the distribution of biomass temperature over the entire volume of the digester. Studies were conducted to obtain data on the impact of the main parameters (design, kinematic and geometric) of a biogas plant and a heat exchanger-agitator on the quality indicators of its work, as well as the thermal processes occurring in it. The theoretical temperature homogeneity of the mixed medium is achieved by combining the heat exchanger and the mixing device into one node, the design and technological parameters of which characterize the intensity of the forced movement of fermented waste, changing the value of thermal conductivity, and finding the temperature field is the main task of the analytical theory of thermal conductivity applicable to the processes occurring in the bioreactor installation.

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1. Introduction

Recently, there has been a trend towards an increase in energy consumption throughout the world. The urgent need is a transition to sustainable energy development based on energy saving and efficient use of new and renewable energy sources.

The main advantages of renewable energy sources are the prospect of preserving energy reserves for future generations while minimizing air pollution and energy independence. For 30 years of practical use of renewable energy in the world, its volume increases annually. Renewable sources provide 19 % of world energy production. At the same time, the share of renewable energy in the fuel balance of Russia is only 1 %.

One of the areas in the provision of cheap energy to agricultural enterprises is the use of agricultural waste (crop, livestock, poultry) by processing biological mass (biomass) and the production of biological gas (biogas) from it and highly efficient bio-fertilizer.

One of the most acute problems in the development of agriculture is the problem of its efficient energy supply. While traditional sources of energy have received a lot of attention, to date, the use of unconventional energy sources has, to date, been rather skeptical. To a greater extent, this attitude was incorporated both by the low cost of traditional energy resources and the relatively low scientific substantiation of the issues of improving the efficiency of non-traditional and alternative energy sources. At present, the picture is changing in the direction of increased attention to the use of alternative energy sources, which is largely due to both the increase in their efficiency and the increase in tariffs for traditional energy resources. In this regard, the relevance of research to improve the efficiency of use of alternative energy sources for farms has increased significantly. Among the most acceptable areas can be considered the use of such unconventional sources as energy derived from biotechnology [1].

2. Materials and Methods

A promising direction for the processing of poultry and livestock waste is anaerobic digestion, which helps to prevent environmental pollution, as well as to obtain processing products: gaseous fuel -- biogas and highly efficient bio-fertilizer [2, 3].

The processing of poultry and animal waste in a biogas plant is carried out by biochemical anaerobic decomposition of organic materials in the absence of oxygen, the flow rate and effectiveness of which depends on the following factors: temperature and mass heating method, acidity, and the degree of mixing. In this regard, biogas plants are equipped with heating, mixing, acidity control, heat recovery, and the bioreactor (methane tank) is insulated [4].

For efficient operation of the bioreactor and maintaining stable fermentation, the feedstock must be heated and periodically mixed to prevent areas of uneven temperature. Also mixing eliminates stagnation of gas bubbles and increases the speed of their ascent.

The purpose of research is to study the thermal processes occurring in a biogas plant operating in a thermophilic mode.

In the laboratory "Alternative Energy" FSBEI HE Kabardino-Balkaria State Agrarian University conducted research work on the design and optimization of operating modes of a biogas plant for agricultural enterprises [5].

To prevent the separation of the mass (substrate) and the intensification of the fermentation process, it is necessary to carry out the stirring of an agitator installed in the digester with both a mechanical and an electric drive. Intensification of heat transfer in the fermented medium is possible when free movement is replaced by forced movement, moreover, within the thermal boundary layer, which determines the patterns of heat transfer, and the frequency of rotation of the stirrer is the determining value of the motion mode.

To intensify the process of fermentation and optimize the design and energy parameters of the digester it is proposed to combine a mixing device (mixer) and a heating element in one node, i.e. mixing device is also a heating element. Such a combination allows you to heat and maintain a given temperature regime more evenly due to the rotation of the heat exchanger and heat transfer to the biomass (substrate) throughout the entire volume of the digester, 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 heat exchangers (water jacket, tubular fixed) which allow only limited areas to be heated, which leads to uneven heating.

Biomass mixing is carried out in 2...3 hours, with a duration of 15...20 minutes, with a rotational speed of 7...8 min^{-1}, and the whole process is controlled by a microprocessor controller -- TPM 202. The heating of the biomass for the flow of the thermophilic process should not exceed 600C. is selected depending on the type of waste being processed.

The bioreactor scheme presented in Figure 1 consists of a sealed, heat-insulated body *1* with a lid *2*, supply nozzles *3* and a biomass outlet *4*, a biogas exhaust nozzle *5*, and a heat exchanger-agitator *6*. Figure 2 shows the arrangement of the blades of a heat exchanger-agitator.

The design of the bioreactor includes a heat exchanger-mixer, made in the form of a vertical shaft with blades of steel pipes, symmetrically and rigidly attached to the shaft, rotating in a horizontal plane, and the upper and lower parts are connected to a heat source.

Due to this design of the bioreactor, the metal consumption of the structure and the energy costs of its operation are reduced, the output of biogas increases due to uniform heat exchange and mixing of biomass throughout the entire bioreactor.

From the heat source, the heated coolant enters the heat exchanger-agitator shaft and is distributed over all its blades, heating the biomass and returning to the heat source through the return pipe. There is a constant heating of the biomass and the circulation of the coolant.

For further theoretical studies, a calculated three-dimensional model of the bioreactor has been developed, presented in Figure 3 and 4 [2].

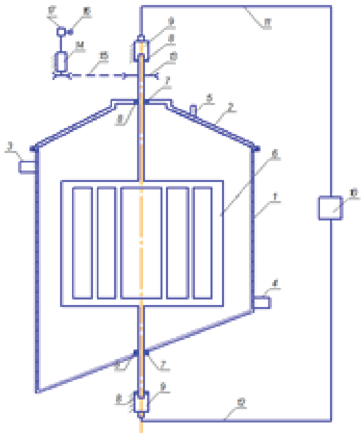

Figure 1: Scheme of the bioreactor with a heat exchanger-mixer. 1 -- housing, 2 -- cover, 3, 4 -- biomass inlet and outlet connections, 5 -- biogas removal pipe, 6 -- heat exchanger-agitator, 7 -- rolling bearing, 8 -- stuffing box, 9 -- cylindrical pipe, 10 -- heat source, 11, 12 supply and return pipes, 13 -- driven pulley, 14 -- electric motor, 15 -- V-belt transmission, 16 -- microprocessor controller, 17 -- software time relay.

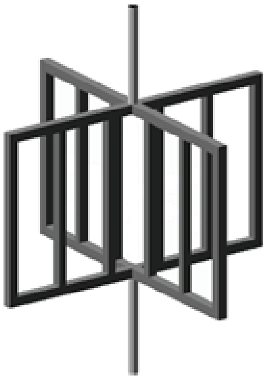

Figure 2: The layout of the blades of the heat exchanger-mixer.

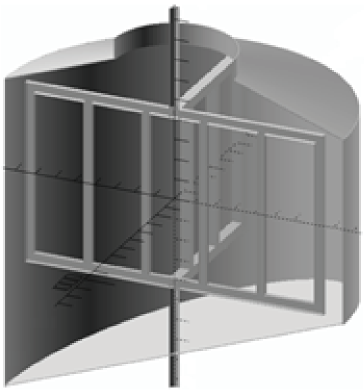

Figure 3: Calculation scheme of the bioreactor.

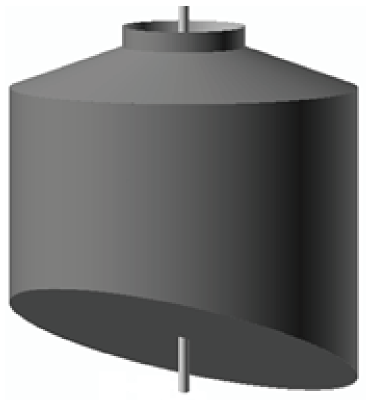

Figure 4: Three-dimensional model of the bioreactor.

3. Results and Discussion

Consider the thermal processes occurring in a biogas plant. Required to operate the unit in a thermophilic mode, after its output to the working state, the thermal power is determined by the heat loss of the unit itself [6]. In the bioreactor, heat exchange processes take place directly in the installation volume with increasing litter temperature to the temperature of the thermophilic mode, which can be described by the equations of thermodynamics.

Theoretical studies of thermal processes occurring in a biogas plant operating in a thermophilic mode, after its withdrawal to the operating state, have been carried out. The required heat output is determined by the heat loss of the installation itself and is described by the equations of thermodynamics.

In particular, to determine the amount of heat passing through the volume of a bioreactor, as follows from the Fourier law, it is necessary to know the internal temperature field of the bioreactor, and finding the temperature field is the main task of the theory of thermal conductivity in relation to the processes occurring in the installation bioreactor [7].

This article presents the results of deriving the differential heat equation, which gives a description of the temperature field in a bioreactor.

When deriving the equation, we accept the following assumptions: -- the bioreactor is homogeneous and isotropic throughout the volume; -- physical parameters are constant; -- the change in the volume of the bioreactor associated with a change in temperature, which can be neglected; -- uniform distribution of internal sources of heat in the volume of the bioreactor.

Mathematical modeling is a very important stage of research, because allows you to imagine the physics of the process taking place in an object. The most accurate and complete model helps to simplify the process of analyzing the dynamic characteristics of a physical phenomenon or a process taking place in a research object -- a bioreactor, if it is verified for adequacy to the actual process. The feasibility of mathematical modeling is due both to the high cost of conducting experiments on a real bioreactor, subject to the need for its design and manufacture, and time-consuming due to the high inertia of thermal processes, for example, the bioreactor, due to the significant overall dimensions of the installation [8--10].

In this case, a joint solution of the equations of heat transfer and mass transfer is necessary. The result of this simulation may be the temperature distribution and concentration of organic particles in the volume of the digester.

The heat source will be a gas boiler. The heated water enters the heat exchanger-mixer of a biogas plant and heat is transferred through the walls of the fermentation mass. Thus, convective heat exchange takes place.

The concept of convective heat transfer encompasses the process of heat transfer when a fluid or gas moves. In this case, heat transfer is carried out simultaneously by convection and thermal conductivity. Convection of heat is always accompanied by heat conduction, since the motion of a liquid or gas inevitably leads to the contact of individual particles having different temperatures.

Convective heat transfer between the flow of a liquid or gas and the surface of a solid is called convective heat transfer. Usually, in engineering calculations, heat transfer is determined; knowledge of convective heat transfer inside a liquid medium can be of indirect interest, since heat transfer inside the liquid also affects heat transfer. The resulting heat flux is always directed towards a decrease in temperature.

Heat transfer is influenced by density, heat capacity, thermal conductivity λ and thermal diffusivity 0, water viscosity index μ, specific heat A, density ρ.

Between particles and layers moving at different speeds, there is always an internal friction force opposing movement. According to Newton's law, this tangential force (referred to the unit surface), which acts at any point of the flow, in a plane oriented along the flow, is proportional to the change in velocity in the direction normal to the direction of motion:

$$s = \mu \frac{\partial w}{\partial n},$$

Thus, the process of heat transfer can be represented as follows. Each particle of water has its own speed, which decreases towards the wall, and for particles adhering to the wall, it is equal to zero. Thus, from moving water to a solid surface, heat passes through a fixed sticking layer. The molar heat transfer prevails transversely to the wall, in the direction of the wall, mainly by convection, and molecular heat transfer prevails at the wall itself due to heat conduction, which allows determining the heat flux through the water layer at the wall according to the Fourier thermal conductivity:

$$q = -\lambda_B \left(\frac{\partial T}{\partial y}\right)_{y=0}$$

where λ_B is the coefficient of thermal conductivity of water, W/(m·K); T -- current temperature, K.

The process of heat conduction takes place if at different points of the bioreactor the temperature of the mass varies. The process of heat propagation in the bioreactor proceeds with a change in temperature both in time and in space. The temperature state of the body is characterized by a temperature field.

Since the temperature at different points in the volume of the bioreactor is determined by the coordinates x,y,z and time τ, in the general case the equation of the temperature field has the form:

$$T = f\,(x, y, z, \tau)$$

There are non-stationary and stationary temperature fields. If the temperature at all points of the bioreactor changes over time, then such a field is unsteady, but if the temperature does not change over time -- the field is steady-state.

The temperature in the bioreactor changes in the direction of the three coordinate axes, and is a three-dimensional (spatial) temperature field, and the equation describes a three-dimensional non-stationary field.

The equation of a three-dimensional stationary field has the form:

$$T = f_1\,(x, y, z)\,,\ \text{i.e.}\ \frac{\partial \mathrm{T}}{\partial \tau} = 0$$

The equation of a one-dimensional unsteady field takes the form:

$$T = f_1\,(x, \tau)\,,\ \text{i. e.}\ \frac{\partial \mathrm{T}}{\partial y} = \frac{\partial \mathrm{T}}{\partial z} = 0$$

The simplest form has the equation of a one-dimensional stationary temperature field:

$$T = f_3\,(x)\,,\ \text{i. e.}\ \frac{\partial \mathrm{T}}{\partial \tau} = \frac{\partial \mathrm{T}}{\partial \mathrm{y}} = \frac{\partial \mathrm{T}}{\partial z} = 0$$

The locus of points in the temperature field of a bioreactor having the same temperature is called an isothermal surface.

Since the same point of the bioreactor does not have different temperatures, the surface of the bioreactor is an isothermal surface.

Figure 5 shows isotherms whose temperatures differ by dT. The temperature in the body changes only in the directions intersecting the isothermal surfaces (direction). In this case, the greatest temperature difference per unit length occurs in the direction normal to the isothermal surface. The ratio of temperature change dT to the distance between the isotherms along the normal dn and $dn \to 0$, is a temperature gradient, that is:

$$gradT = \lim_{dn \to 0} \left(\frac{dT}{dn} \right) = \frac{dT}{dn}$$

The temperature gradient is a vector quantity, while the direction in the direction of increasing temperature is taken as the positive direction of vector $gradT$, and the scalar quantity $gradT$ is called the temperature gradient, which is not the same for different points of the isothermal surface of the bioreactor.

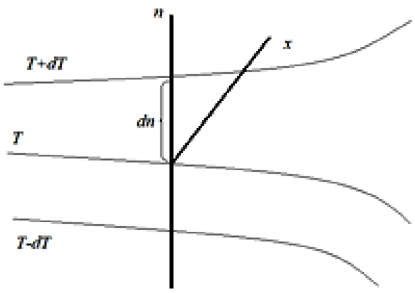

Figure 5: Isotherms.

The projections of vector $gradT$ on the coordinate axes $0x, 0y, 0z$ are:

$$(gradT)_x = \frac{\partial T}{\partial n_x} \cos\left(n_x x\right) = \frac{\partial T}{\partial x}$$

$$(gradT)_y = \frac{\partial T}{\partial n_y} \cos\left(n_y x\right) = \frac{\partial T}{\partial y}$$

$$(gradT)_z = \frac{\partial T}{\partial n_z} \cos\left(n_z x\right) = \frac{\partial T}{\partial \text{z}}$$

The basic law of heat propagation by thermal conductivity is the Fourier law, according to which the amount of heat $dQ(\tau)$, passing through an element of an isothermal surface dF over a period of time $d\tau$, is proportional to the temperature gradient $\partial T / \partial n$:

$$dQ(\tau) = -\lambda \cdot \frac{\partial T}{\partial n} dF \cdot d\tau, [\text{где}]$$

The coefficient of proportionality λ in the equation is a parameter characterizing the ability of the body to conduct heat, that is, is the coefficient of thermal conductivity.

Heat flux passing through the isothermal surface of bioreactor dF:

$$dQ = \frac{dQ(\tau)}{d\tau} = -\lambda \cdot \frac{\partial T}{\partial n} dF, [Bm]$$

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The heat flux density passing through the isothermal surface of the bioreactor:

$$q = \frac{dQ(\tau)}{dF \cdot d\tau} = -\lambda \cdot \frac{\partial T}{\partial n}, \left[\frac{Bm}{\mathscr{M}^2}\right]$$

The heat flux density in the bioreactor has a positive direction of the vector, since it is directed towards its isothermal surface with decreasing temperature, and the vectors q and $gradT$ lie on the same straight line, however, they have opposite directions. Hence the minus sign in these equations.

Accordingly, these equations are the Fourier law written for heat, for heat flux, and for heat flux density in a bioreactor.

For all the heat passed during time τ through an isothermal surface, the Fourier law in integral form represents the form:

$$Q(\tau) = -\int_0^{\tau}\int_F \lambda \frac{\partial T}{\partial n} dF d\tau, [\text{где}]$$

For heat flow:

$$Q(\tau) = -\int_F \lambda \frac{\partial T}{\partial n} dF = \int_F q dF, [Bm]$$

If the heat flux density vector is projected onto the $0x, 0y, 0z,$ coordinate axes, we get:

$$q_x = -\lambda \frac{\partial T}{\partial x}, q_y = -\lambda \frac{\partial T}{\partial y}, q_z = -\lambda \frac{\partial T}{\partial z}$$

As mentioned earlier, the coefficient of thermal conductivity λ is a physical parameter of biomass characterizing the ability to conduct heat. In this case, λ depends on the type of biomass, pressure and temperature. Basically, the thermal conductivity coefficient is determined empirically when measuring the heat flux density and $gradT$ in the mass under study. The coefficient of thermal conductivity λ is determined from the relationship:

$$|\lambda| = \frac{|q|}{|gradT|}, \left[\frac{Bm}{\mathscr{M} \cdot \text{K}}\right]$$

From this equation the physical meaning of the thermal conductivity coefficient is formulated.

4. Conclusion

Experiments show that the dependence of thermal conductivity on temperature, with enough accuracy for many materials, can be taken linear:

$$\lambda = \lambda_0 (1 \pm bT)$$

where: λ_0 -- the value of thermal conductivity at $T = 0^0C$; b -- a constant value determined experimentally.

If we consider the change in the thermal conductivity of various substances, we can say the following.

The coefficient of thermal conductivity of liquids ranges from 0,07 to 0,7 $\left[\text{В} / (\mathscr{M} \cdot \text{К}) \right]$. In many liquids, except for water and glycerin, the heat conduction decreases with increasing temperature. With increasing pressure, the thermal conductivity of liquids increases.

In metals, the main carrier of heat is free electrons, which can be likened to an ideal monatomic gas. With increasing temperature, the scattering of electrons increases due to an increase in thermal inhomogeneities, which leads to a decrease in the thermal conductivity of metals. In dielectrics, with increasing temperature, thermal conductivity usually increases, but it strongly depends on humidity, porosity, and material structure.

From the Fourier law it follows that to determine the amount of heat passing through the volume of a bioreactor, it is necessary to know the temperature field inside the bioreactor itself. Finding the temperature field is the main task of the analytical theory of thermal conductivity in relation to the processes occurring in the installation bioreactor.

Analysis of the above equations shows that heat conduction, thermal diffusivity, density and structural and technological parameters of the heat exchanger stirrer, which characterizes the intensity of the forced movement of the fermented litter, affect the value of thermal conductivity.

Thus, the mixing time and, consequently, the degree of temperature homogeneity of the fermented material (litter or manure) depends on the multiplicity of circulation of biomass in the installation.

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