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Heat Balance of a Cylindrical Biogas Reactor

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ABSTRACT*. *Introduction.
The reduction of traditional energy resources in the world and the regular increase in their cost indicate the importance of using energy-saving technologies in future cargo transportation. In three articles, the authors proposed a heat balance of a bioactor with high thermal performance.

Method and materials.
In this article, methods such as technical thermodynamics, hydrodynamics, heat exchange theory and mathematical modeling are used to determine the hydrodynamic and heat exchange processes occurring in bioreactors and heat exchangers.

Results.
The heat balance equations of the bioreactor are created taking into account the amount of heat entering the bioreactor during the heating of the biomass and released during the exothermic reaction of anaerobic fermentation. A graph of the dependence of the biomass temperature on the heat carrier entering the bioreactor is obtained, from which it is evident that the duration of heating decreases depending on the temperature of the heat carrier entering the bioreactor.

Conclusion.
The heat balance equations compiled by the authors based on the heat balance scheme of the bioreactor make it possible to determine the heat exchange surface of bioenergy devices with different parameters, the amount of biogas released daily and the heat load.

I. INTRODUCTION

It is relevant to select the optimal parameters of biogas plants and justify their efficiency in reducing energy consumption in the process of processing biomass raw materials. Biomass is a renewable energy source with a high potential reserve, through which biogas (CH_4) can be obtained, and heat and electricity can be generated from it. The Strategy for Innovative Development of the Republic of Uzbekistan for 2019-2021 sets out target indicators for the innovative development of our country until 2030, and also pays special attention to the effective use of renewable energy sources (RES). Currently, great attention is being paid to the introduction of RES in our country. Energy plants operating on the basis of renewable energy sources can be equipped with devices for obtaining biogas - an alternative fuel in a biological way. Biomass can be used to produce biogas, which contains from 50 to 75 percent methane (CH_4). It can be used to generate heat and electricity, as well as for cooking, hot water, and heating [1, 2].

According to statistics, there are more than 6,000 farms in Uzbekistan, with more than 650,000 cattle and 21 million poultry, which generate more than 6 million tons of organic waste per year. Only 23,000 tons of this organic waste are recycled, which is 0.4% of the total [3].

Biomass processing provides the opportunity to obtain biogas (biomethane) and high-quality biofertilizer for agriculture. Biomass processing, firstly, creates the opportunity to utilize (recycle) agricultural and local organic waste, secondly, to obtain cheap biofuel, thirdly, to obtain high-quality biofertilizer for agriculture, and fourthly, to solve such urgent problems as reducing the amount of harmful emissions into the atmosphere.

Analysis of biomass energy generation devices shows that it is necessary to solve problems such as reducing the energy consumption of the raw material processing process, optimizing the energy balance of the device, and increasing its energy efficiency [4].

The heat balance of the bioreactor was constructed taking into account the amount of heat entering the bioreactor during the biomass heating process and released during the exothermic reaction of anaerobic fermentation. The resulting equations allow determining the heat exchange surface (surface area) and the design parameters of the heat exchange device.

One of the main factors affecting the efficiency of the biogas production process is the temperature of the liquid biomass in the bioreactor. It is known that the temperature in the anaerobic fermentation process is variable, and it is necessary to maintain a constant temperature of the biomass throughout the process [5, 6]. Heat exchangers of various designs are used to maintain the temperature in biogas production reactors. In particular, heat exchangers made in the form of a tube-tube are widely used [7, 8].

II. METHODS AND MATERIALS

The article uses methods of mathematical modeling of hydrodynamic and heat exchange processes occurring in bioreactors and heat exchange equipment. The differential equation is reduced to the Cauchy problem by setting the terms constituting the bioreactor heat balance, and the change in biomass temperature over time is found using the Euler method based on the initial condition $t_{bm} = t_{bm.0} = t_{out}$ at τ=0.

The bioreactor consists of determining the surface area of the heat exchange surface $F_{br.surf}$ (m^2), Q_{br} (W) - depends on the heat load of the bioreactor and is determined from the basic heat transfer equation [9, 10]:

$$Q_{br} = k_{br} \cdot F_{br.surf} \cdot \Delta t_{aver} = G_s \cdot c_s \cdot (t_s^{'} - t_s^{''}) \text{ , Vt} \quad (1)$$

from this

$$F_{br.surf} = \frac{Q_{br}}{k_{br} \cdot \Delta t_{aver}} \text{ , } \mathrm{m}^2 \quad (2)$$

here, Q_{br} – amount of heat transferred by the cooling water, W; k_r – heat transfer coefficient from the heat carrier to the biomass, W/(m^2·K); Δt_{aver} – average temperature difference; $t_s^{'}, t_s^{''}$ – heat carriers, temperatures at the inlet and outlet of the bioreactor heat exchanger, ^{0}C; G_s – flow rate of heat carrier (water), kg/sec; c_s – specific heat capacity of the heat carrier, J/kg*^{0}C.

To determine the heat load, it is necessary to draw up a heat balance of the device. When producing biogas from biomass, we draw up the heat balance equation of the bioreactor according to the calculation scheme in Figure 1.

The general form of the heat balance equation, taking into account heat losses to the environment, is expressed by the following equation:

$$\sum Q_{sup} = \sum Q_{con} + Q_{lost} \text{ , W} \quad (3)$$

here, Q_{sup} – the amount of heat supplied to the device, W; Q_{con} – the amount of heat consumed by the device, W; Q_{lost} – the amount of heat lost to the environment, W.

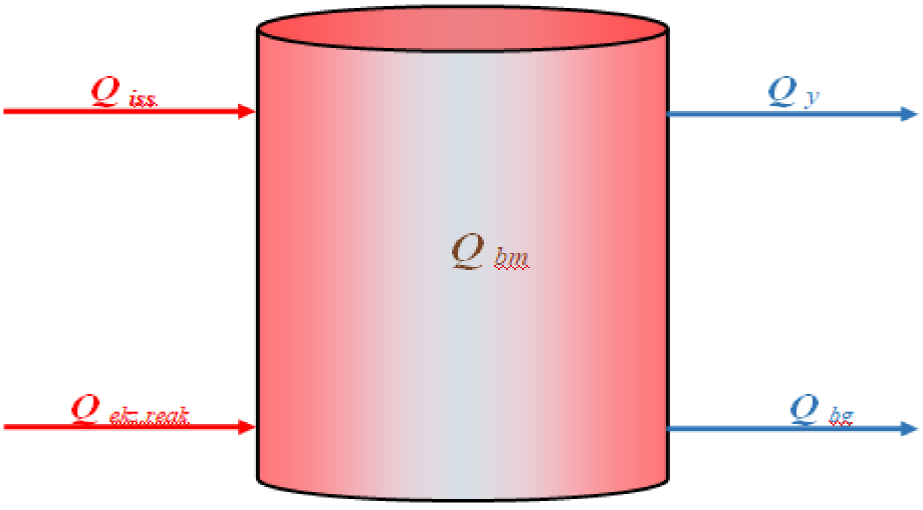

Figure 1. Heat balance diagram of a bioreactor.

The amount of heat supplied to the bioreactor is determined by the following expression:

$$\sum Q_{sup} = Q_{subs.sup} + Q_{exo.reac} + Q_r \text{ , W} \tag{4}$$

here, $Q_{subs.sup}$ – the amount of heat supplied by the substrate, W; $Q_{exo.reac}$ – the amount of heat released during the exothermic reaction of anaerobic fermentation, W.

The amount of heat carried along with the substrate is determined as follows:

$$Q_{subs.sup} = \frac{c \cdot v \cdot \rho \cdot t_{bm.d}}{86400} \quad \text{, W} \tag{5}$$

here, v – the initial biomass volume, m^3; ρ – the biomass density, kg/m^3; c – the heat capacity of biomass, J/kg·K; t_{sup} – the initial temperature of biomass, K.

The amount of heat released during the exothermic reaction of anaerobic fermentation depends on the content of absolutely dry matter in the total volume of biomass:

$$Q_{exo.reac} = \frac{E_{exo.reac} \cdot m_{dry}}{86400} \text{ , W} \tag{6}$$

here, $E_{exo.reac}$ – the thermal energy released from 1 kg of absolutely dry biomass, $E_{exo.reac}$ = 1,5 MJ [11, 12]; m_{dry} – the mass of absolutely dry biomass, kg.

The amount of heat released from the bioreactor is determined by the following expression:

$$\sum Q_{con} = Q_{lost} + Q_{bg} \text{ , } \quad \text{W} \tag{7}$$

here, Q_{lost} – the amount of heat lost by the processed biomass, W; Q_{bg} – the amount of heat lost by the produced biogas, W.

The amount of heat lost by processed biomass is determined as follows:

$$Q_{lost} = \frac{c v_{leav} \rho t_{leav}}{86400} \text{ , W} \tag{8}$$

here, v_{leav} – the volume of biomass leaving the bioreactor, m^3; t_{leav} – the temperature of the processed biomass, K.

The amount of heat lost by the produced biogas is determined as follows:

$$Q_{bg} = \frac{c_{bg} V^{'} \rho_{bg} t_{bg}}{86400} \text{ , } \quad \text{W} \tag{9}$$

here, c_{bg} – the heat capacity of biogas, J/kgK; $V^{'}$ – the daily volume of biogas produced, m^3/day; ρ_{bg} – the density of biogas, kg/m^3; t_{bg} – the temperature of biogas produced, K.

The amount of heat lost to the environment by the bioreactor depends on the environmental temperature and is determined as follows:

$$Q_{br.wall} = k_{wall} F_{br.surf} (t_{bm} - t_{envi}) \text{ , } \quad \text{W} \tag{10}$$

here, k_{wall} – the heat transfer coefficient to the environment, W/(m^2 K); $F_{br.surf}$ – the area (surface) of the bioreactor wall, m^2; t_{bm} – the temperature of the biomass in the bioreactor, K; t_{envi} – the environmental temperature, K.

Using equations (4-7), we determine the heat load of the bioreactor:

$$Q_r = Q_{subs.sup} + Q_{exo.reac} - Q_{lost} - Q_{bg}, \quad \text{W} \tag{11}$$

Taking into account equation (1-11), we write the differential equation expressing the change in biomass temperature over time as follows:

$$c_{bm} \cdot m_{bm} \cdot \frac{dt_{bm}}{d\tau} = G_s \cdot c_s \cdot \left(t_s^{'} - t_s^{''}\right) + \frac{E_{exo.reac} \cdot m_{dry}}{86400} -$$

$$- k_{wall} F_{br.surf} (t_{bm} - t_{envi}) - \frac{c_{bg} V^{'} \rho_{bg} t_{bg}}{86400} \text{ , } \quad \text{W} \tag{12}$$

Based on the initial condition $t_{bm} = t_{bm.0} = t_{out}$ at $\tau = 0$, the solution to equation (13) can be written as follows:

$$t_{bm} = t_{bm.0} \cdot \exp\left(-\frac{k_{wall} F_{br.surf} + \frac{c_{bg} V^{'} \rho_{bg}}{86400}}{c_{bg} \cdot m_{bm}} \cdot \tau\right) +$$

$$+ \left(1 - \exp\left(-\frac{k_{wall} F_{br.wall} + c_{bg} V^{'} \rho_{bg}}{c_{bg} \cdot m_{bm}} \cdot \tau\right)\right) \cdot$$

$$\cdot \frac{G_s \cdot c_s \cdot \left(t_s^{'} - t_s^{''}\right) + \frac{E_{exo.reac} \cdot m_{dry}}{86400} + k_{wall} F_{br.surf} \cdot t_{envi}}{k_{wall} F_{br.surf} + c_{bg} V^{'} \rho_{bg}} \text{ , } {}^{0}\text{C} \tag{13}$$

III. RESULTS

We present the values of the parameters in equation (13) in Table 1 and the change in biomass temperature over time for different coolant temperatures in Figure 2.

Table 1

Table of thermal and technical parameters of the bioreactor.

№	**Parameters**	**Description**	**Unit of measurement**	**Value**
1	Biogas density	ρ_{bg}	kg/m^3	1020
2	Bioreactor volume	$V_{reactor}$	m^3	0.5 m^3
3	Daily volume of biogas produced	$V^{'}$	m^3/day	0.35 m^3
4	Optimal temperature of the bioreactor	$dt_{reactor}$	℃	52-56 ^{0}C
5	Heat transfer coefficient to the environment	k_{envi}	$W/m^2 \cdot K$	42.8
6	Outside air temperature	t_{out}	℃	10 ^{0}C
7	Bioreactor heat exchange surface area	$F_{br.surf}$	m^2	11,52
8	Biogas heat capacity	c_{bg}	$J/kg \cdot ℃$	2080
9	Biomass heat capacity	c_{bm}	$J/kg \cdot ℃$	4080

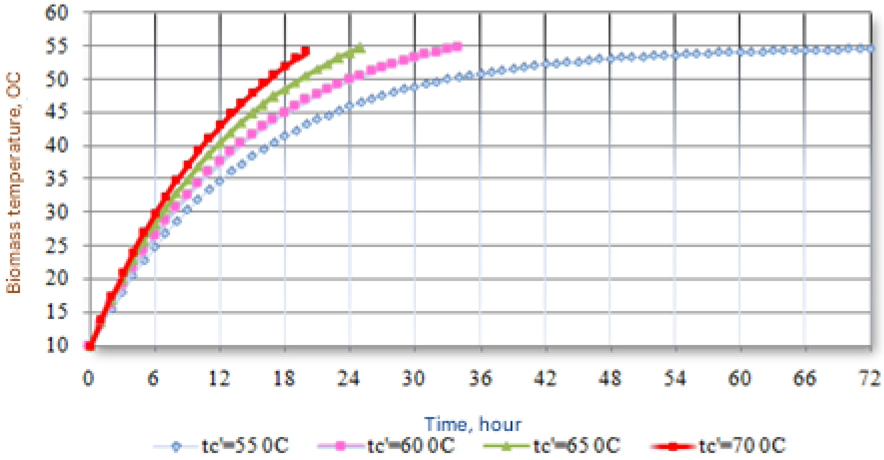

Figure 2. The dependence of the change in biomass temperature over time on the heat carrier entering the bioreactor.

IV. CONCLUSIONS

The temperature of the heat carrier in the bioreactor depends on the duration of biomass accumulation, and when the biomass temperature rises to 55 °C, the heat supplied must be sufficient to overcome the heat loss through the walls of the bioreactor device.

It can be seen from Figure 2 that the duration of the combustion decreases depending on the temperature of the heat carrier at the inlet to the bioreactor. Given that the initial temperature of the biomass is 10 °C, it can be seen that the temperature of the heat carrier at the inlet to the bioreactor is $\tau = 57\ hours$ at $t_s^{'} = 55$ ℃; $\tau = 34\ hours$ at $t_s^{'} = 60$ ℃; $\tau = 25\ hours$ at $t_s^{'} = 65$ ℃; $\tau = 20\ hours$ at $t_s^{'} = 70$ ℃.

Usually, in the problems considered, the initial and final temperatures of the heat carrier are known. Accordingly, the values of the quantities G_s, τ, m_{bm} can also be given or estimated. In this case, using expression (2), the heat exchange surface $F_{br.surf}$ can be determined. In this case, the heat transfer coefficient is calculated taking into account the specific conditions of heat transfer, as in continuous-flow devices.

Based on the obtained equations (2, 9, 11), it is possible to determine the area of the heat exchange surface, the amount of biogas released per day, and the heat load.

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