Study of the parameters of biogas plants

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Abstract. The peculiarity of renewable sources is their replenishment. To ensure energy security and correctly use land resources, it is possible to use biogas plants, which are renewable sources. However, efficient use of these installations turns out to be a difficult task that requires a comprehensive assessment of the parameters of their operation. In the example under consideration, such parameters are: the choice of the power of the heating equipment of the installation and the determination of the temperature stability of operation in case of a violation of the technological process. One of the important results of the study is that the power for heating biomass in the mesophilic mode with continuous and periodic processes is selected according to the start-up mode, and for the thermophilic mode with the periodic process, the power for heating is determined by the start-up mode, and in the continuous process - by the steady-state mode. The study also provides a calculation of thermal stability for reactors of different volumes at different degrees of their filling with biomass, taking into account the operating temperatures of the biogas plant.

1. Introduction

Agriculture is an important industry that ensures the food security of the state. One of the main problems faced by agricultural production is the utilization of the resulting waste in the life of animals and birds. This problem can be successfully dealt with by biogas technology related to renewable energy sources [1-5]. These sources are inexhaustible and provide development prospects [4-7].

Biogas plants make it possible to utilize waste from livestock and poultry farming, reducing the land area for storing this waste and ensuring environmental safety. The resulting combustible gas can be used for own needs, thus it reduces the cost of the biowaste utilization process [1,2,5,7-12].

At the same time, the use of biogas plants (BGP) in Russia is contained by many factors, including the lack of development in the design methodology, which would take into account not only climatic conditions, but operating modes [1,2,12-17]. When designing a biomass plant, it is important to select the heating power, taking into account the mode of its operation, as well as the choice of design parameters of the installation, depending on the possible cooling degree of the fermented biomass (substrate) in the event of a disruption in the technological process [11,12,14-19].

Purpose: the research of the biomass operation mode to select the installation design parameters and the required heating power, as well as the degree of possible cooling of the fermented biomass in the case of a disruption in the technological process.
2. Materials and research methods

The power to cover the heat loss in the reactor can be defined as [1,2,16-21]:

\[ Q_{\text{losses}} = kS\Delta t_{\text{losses}}, \text{W} \] (1)

where \( k \) is the heat transfer coefficient, \( \frac{W}{m^2 \cdot K} \), \( S \) is the reactor heat transfer surface area, \( m^2 \); \( \Delta t_{\text{losses}} \) is the temperature difference inside the reactor and outside air, \(^\circ\text{C}\).

In the start-up mode, stable growth of microorganisms in an anaerobic environment is possible with gradual heating of the loaded raw material, no more than 2\(^\circ\text{C}\) per 24 hours, and bringing it to the required fermentation temperature [1,2,13,17-20]. In this case, the required power depends on a number of factors:

\[ P_{\text{increased}} = f(V_\text{z}, \tau_{\text{increased}}, \Delta t_{\text{increased}}), \text{W} \] (2)

where \( V_\text{z} \) is the volume of filling the reactor with biomass at the start of the biomass unit, \( m^3 \); \( \tau_{\text{increased}} \) is the time of gradual heating of the substrate, \( s \); \( \Delta t_{\text{increased}} \) is the temperature difference at the beginning and at the end of daily heating in start-up mode, \(^\circ\text{C}\).

The power for heating the daily dose of the substrate with continuous loading of the bioreactor depends on the volume and temperature, as well as the heating time [16,18,20-25]:

\[ P_{\text{daily dose}} = f(V_{\text{daily dose}}, \tau_{\text{daily dose}}, \Delta t_{\text{daily dose}}), \text{W} \] (3)

where \( V_{\text{daily dose}} \) is the biomass daily dose volume, \( m^3 \); \( \tau_{\text{daily dose}} \) is heating time of the daily dose to the set temperature, \( s \); \( \Delta t_{\text{daily dose}} \) is the temperature difference between the inside of the reactor and the loaded daily substrate, \(^\circ\text{C}\).

The required power in the starting mode can be represented as:

\[ P_{\text{start}} = P_{\text{increased}} + Q_{\text{losses}}, \text{W}. \] (4)

The required power in a steady-state biomass fermentation mode, with a continuous biomass loading process [1,2,12,16,17,18,24]

\[ P_{\text{steady state continuous}} = P_{\text{daily dose}} + Q_{\text{losses}}, \text{W}. \] (5)

Power, in steady state, with periodic loading of biomass [17-20]:

\[ P_{\text{steady state periodic}} = Q_{\text{losses}}, \text{W} \] (6)

During the design of a bioreactor, it is necessary to determine the highest power consumption in the considered modes, depending on the loading process and design parameters of the bioreactor. To carry out the necessary research, we introduce an indicator that allows us to evaluate the power ratio in steady state and start-up modes:

\[ \gamma = \frac{P_{\text{start}}}{P_{\text{steady state}}}. \] (7)

When designing a biomass plant, it is important to determine the permissible limits of biomass cooling in the event of a disruption in the technological process, when the heating mode is stopped. Cooling conditions can be represented by the following equation:

\[ \Theta = \Theta_0 \times e^{-t/\tau}, \] (8)

where \( \Theta \) is an excess body temperature over ambient temperature, \(^\circ\text{C}\); \( \Theta_0 \) is an initial temperature rise, \(^\circ\text{C}\); \( t \) is cooling time, \( s \) (min., hours); \( \tau \) is constant cooling, \( s \) (min., hours).

The reactor cooling constant is the time during which the temperature rise of the substrate over the ambient temperature, changing exponentially, decreases by a factor of "e". For a homogeneous body, it has the following dependence:

\[ T = \frac{Gx}{S \times k}. \] (9)
where $G$ is body mass, kg; $c$ is specific heat, $\frac{J}{kg \times K}$; $S$ is a heat transfer area of a biogas plant reactor, $m^2$; $k$ is a heat transfer coefficient, $\frac{W}{m^2 \times K}$.

For a reactor, taking into account its filling with a substrate, the cooling constant can be represented as:

$$T = \frac{G \times c}{S_1 \times k_1 + S_2 \times k_2},$$

(10)

where $G$ – substrate weight, kg; the density of the substrate is taken to be equal to the density of water; $c$ is specific heat, $\frac{J}{kg \times K}$; $k_1$ is a coefficient of heat transfer from organic matter through the wall of the reactor to the outside air, $\frac{W}{m^2 \times K}$; $S_1$ is a heat transfer surface area for organic matter, $m^2$; $k_2$ is a heat transfer coefficient from biogas through the reactor wall to the outside air, $\frac{W}{m^2 \times K}$; $S_2$ is a heat transfer surface area for biogas, $m^2$.

The higher the temperature of the fermentation process, the more stringent the requirements for the permissible temperature fluctuations for optimal gas formation: with mesophilic - ± 1 °C per hour; thermophilic - ± 0.5 °C per hour [18-23]. The shift of the cooling temperature from the area of one biomass fermentation process to the temperature range of another process should also be considered a violation of the requirements for the choice of parameters of biogas plants, since the family of already existing bacteria may not survive at other temperatures.

3. Research results and their discussion

3.1 Discussion of the research results of the relationship between the biogas plants parameters

Let’s take into consideration a biogas plant with a 100 m$^3$ vertical fermentation reactor operating in the mesophilic (32°C) and thermophilic (55°C) range of biomass fermentation temperatures, in a continuous and batch process of biomass fermentation with a 70-90% filling of the reactor [18-23]. Let's take the range of ambient air temperature from 20°C to -20 °C, respectively, the initial temperature of the biomass is taken to be 20°C and 10°C.

Figures 1 and 2 show the results of the study of the coefficient $\gamma$ in the mesophilic and thermophilic regimes of the reactor per 100 m$^3$, respectively, depending on the thickness of the reactor insulation at a given ambient temperature.

Figure 1. Dependence of the power ratio in the mesophilic mode on the thickness of the bioreactor insulation and the ambient temperature.
In the mesophilic mode, from the data in Figure 1, it can be seen that under conditions of periodic loading of biomass, with an increase in insulation thickness at an ambient temperature of 20 °C, the ratio of starting power to power in steady state (coefficient $\gamma$ according to formula 7) is in the range 1.48 - 13.84. Under conditions when the ambient temperature is (-20 °C), the $\gamma$ coefficient changes to a lesser extent, and ranges from 1.11 to 3.96. The less increasing nature of the $\gamma$ coefficient at (-20 °C) is explained by an increase in heat losses and an increase in power consumption in a steady state. The highest values of the coefficient $\gamma$ correspond to 90% of the occupancy of the bioreactor. Under conditions of continuous biomass loading, with an increase in insulation thickness, the change in the $\gamma$ coefficient also has an increasing character and is in the range from 1.02 to 2.26. In this process, a smoother increase in $\gamma$ is observed, since in the steady state power is consumed to heat the daily dose of the substrate (formula 5).

Thus, the obtained dependences in the mesophilic mode show that the choice of the heater power must be carried out according to the data of the starting mode of the fermentation process. In this case, the ambient temperature and the bioreactor occupancy should be taken into account to determine the heater power in the start-up mode.

![Figure 2](image.png)

**Figure 2.** Dependence of the power ratio in thermophilic mode on the thickness of the insulation and the specified ambient temperature.

Analysis of the data in the thermophilic mode (Figure 2) shows that in a periodic process with an increase in the insulation thickness, the coefficient $\gamma$ increases and it is in the range from 1.07 to 5.4 and less than in the mesophilic mode with a periodic loading of the reactor, since with a thermophilic regime increased heat losses, which are reflected in the coefficient $\gamma$. The choice of the heater power for a batch process is carried out according to the start-up mode data. However, for a continuous process, the choice of heating power will be equal to the power of the steady state, since the coefficient $\gamma$ is less than unity.

We will also consider a biogas plant with a 10 m$^3$ vertical fermentation reactor operating in the mesophilic and thermophilic range of biomass fermentation temperatures, in a continuous and batch process of biomass fermentation with a 70-90% filling of the reactor. We will take the range of ambient air temperatures from 20°C to (-20°C) (respectively, the initial temperature of the biomass is taken to be 20°C and 10°C).
Figures 3 and 4 show the results of the study of the coefficient $\gamma$ in the mesophilic and thermophilic processes of a 10 m$^3$ reactor, respectively, depending on the thickness of the reactor insulation at a given ambient temperature.

Figure 3 shows a similar character of the dependence of the coefficient $\gamma$ in comparison with Figure 1, the difference is only in its range. The choice of heating power for biogas plant is also carried out according to the starting power. It is important to note here that for a batch process of loading the reactor at (-20°C), the values of the $\gamma$ coefficient are practically superimposed on the values of the $\gamma$ coefficient of the continuous process at 20°C.

![Figure 3. Dependence of the power ratio in the mesophilic mode on the thickness of the bioreactor insulation and the ambient temperature.](image)

According to Figure 4, with an increase in the thickness of the insulation, the periodic process changes in the range from 1.035 to 3.04. The choice of the power of the heating equipment for a batch process is carried out according to the starting power, for a continuous process it’s carried out according to the power of the steady state.
Figure 4. Dependence of the ratio of powers in the thermophilic mode on the thickness of the insulation and the specified ambient temperature.

3.2 Discussion of the results of the thermal stability of the fermentation process research

From literary sources it is known that the average temperature level for the development of mesophilic bacteria is from 30°C to 40°C; for thermophilic bacteria from 45°C to 85°C [1,2,11,12-23]. To assess the time of permissible cooling, the initial excess of the process temperature over the ambient temperature is important [22-25]. It would be incorrect to compare the cooling times of thermophilic and mesophilic processes, if we do not take into account the possible run in temperature ranges of these bacteria.

To determine the reliability of a biogas plant reactor from the point of view of temperature stability, let’s consider a vertical reactor of 100 m³ when it is filled with a substrate by 70 and 90% at mesophilic and thermophilic temperature regimes of fermentation. Let's assume that the ambient temperature is -20°C.

Figures 5 and 6 show the results of a study of biomass cooling in a 100 m³ reactor in a mesophilic process at 90% and 70% loading, respectively, depending on the insulation thickness (no insulation and 40 mm insulation) of the reactor.

Figures 5 and 6 show that the biomass cooling line in a 100 m³ reactor lies to the right (above) the limit of the permissible temperature drop within the fermentation temperature range, which indicates that even without insulation, a 100 m³ reactor can withstand a temperature jump. However, it should be remembered that mesophilic bacteria are characterized by a range from 30 to 40°C [18-22]. Therefore, marking on the temperature axis 50°C (the temperature rise inside the reactor over the ambient temperature) and keeping this value parallel to the time axis until it intersects with the graphs, we find that for the mesophilic process of biomass fermentation with an initial excess of 52°C in the absence of insulation, a temperature range of no more than 5 hours. In the example with insulation for 90% filling of the reactor, the holding time to the temperature limit of the range is 20 hours, for 70% of the filling of the reactor, it’s 15 hours.
Figure 5. Dependence of biomass cooling in the mesophilic process at 90% loading depending on the insulation thickness (no insulation and 40mm insulation) of the reactor.

Figure 6. Dependence of biomass cooling in the mesophilic process at 70% loading depending on the insulation thickness (no insulation and 40mm insulation) of the reactor.

Figures 7 and 8 show the results of a study of biomass cooling in a 100 m³ reactor in a thermophilic process at 90% and 70% loading, respectively, depending on the insulation thickness (no insulation and 40 mm insulation) of the reactor.

According to Figures 7 and 8, it can be seen that the biomass cooling lines for variants with no insulation lie to the left (below) to the limit of the decrease of permissible temperature within the fermentation temperature range, which indicates that without insulation, a 100 m³ reactor under thermophilic mode does not withstand a temperature jump. The version with insulation provides exposure to a temperature jump, and there is a reserve of more than 50 hours up to the fermentation temperature of thermophilic bacteria in case of a malfunction of the installation.

Figure 7. Dependence of biomass cooling in a thermophilic process at 90% loading depending on the insulation thickness (no insulation and 40mm insulation) of the reactor.

Figure 8. Dependence of biomass cooling in a thermophilic process at 70% loading depending on the insulation thickness (no insulation and 40mm insulation) of the reactor.

To determine the reliability of the reactor of a biogas plant from the point of view of temperature stability, we also consider a vertical reactor of 10 m³ when it is filled with a substrate by 70 and 90% at mesophilic and thermophilic temperature regimes of fermentation. Let's take the ambient temperature (-20 °C).
Figures 9 and 10 show the results of a study of biomass cooling in a 10 m³ reactor in a mesophilic process at 90% and 70% loading, respectively, depending on the insulation thickness (no insulation and 40 mm insulation) of the reactor.

Analysis of the data shows that the biomass cooling lines for the variants with no insulation lie to the left (below) the limit of the permissible temperature decrease within the fermentation temperature range, which indicates that without insulation, a 10 m³ reactor in the mesophilic mode does not withstand a temperature jump. The version with insulation provides exposure to a temperature jump, and there is a 10-hour reserve up to the fermentation temperature limit of thermophilic bacteria when the reactor is 70% and 90% full.

Figures 11 and 12 show the results of a study of biomass cooling in a 10 m³ reactor in a thermophilic process at 90% and 70%, respectively, at loading depending on the insulation thickness (no insulation and 40 mm insulation) of the reactor.

According to Figures 11 and 12, it can be seen that the biomass cooling lines for variants with no insulation lie to the left (below) the limit of decrease of the permissible temperature within the fermentation temperature range, which indicates that without insulation, a 10 m³ reactor under thermophilic mode does not withstand a temperature jump. The version with insulation provides exposure to a temperature jump, and up to the fermentation temperature limit of thermophilic bacteria there is a 50-hour margin when the reactor is 90% full and a 40-hour margin when the reactor is 70% full.
4. Conclusions

The results of the carried out research allow us to lead to the following main conclusions:

1) Power for heating biomass in a mesophilic mode with continuous and batch processes is selected according to the start-up mode (on the graphs, $\gamma$ values are higher than unity); For a thermophilic mode with a periodic process, the power for heating is determined by the start-up mode, and in a continuous process - by the steady-state mode;

2) With an increase in the reactor insulation thickness in the mesophilic mode during a periodic process, the $\gamma$ coefficient grows faster than $\gamma$ in the thermophilic mode during the periodic operation of the installation, since in the thermophilic mode the heat losses increased, that are reflected in the $\gamma$ coefficient; With an increase in the thickness of the insulation during thermophilic fermentation, the coefficient $\gamma$ decreases with the continuous operation of the biogas plant, since the value of the heat loss of the reactor of the installation decreases and the nature of this dependence is strongly related to the power of the daily loading dose that appears in formula (5);

3) Based on these examples of thermal stability of the operation of biogas plant reactors, we can determine that a reactor with a large fermentation volume is characterized by a large thermal inertia in the case of a disruption in the technological process of the installation. The initial fermentation temperature is important to determine the time to get off the fermentation temperature range.

A comprehensive analysis of the plant operation will allow to work out a biogas plant design methodology and recommendations for the operation of existing plants for their more efficient use with the required degree of reliability in case of disruptions to the technological process.

References

[1] Sheryazov S K, Ptashkina-Girina O S 2017 Estimation of renewable energy resources for heat supply systems International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM) 1-6 DOI: 10.1109/ICIEAM.2017.8076239

[2] Sheryazov S K, Ptashkina-Girina O S, Guseva O A 2019 Renewable Low-Potential Thermal Energy Investigation of Water Bodies International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM) 1-6 DOI:10.1109/FarEastCon.2019.8934199

[3] European Commission 2014 Brussels: a policy framework for climate and energy in the period from 2020 to 2030 (COM (2014) 15 final) Commission of the European Communities

[4] Scarlat N, Fahl F, Dallemant J-F, Monforti F, Motola V 2018 A spatial analysis of biogas potential from manure in Europe Renewable and Sustainable Energy Reviews 94 915-30
[5] Scarlat N, Dallemand J-F, Fahl F 2018 Biogas: Developments and perspectives in Europe Renewable Energy 129 457-72
[6] Sheryazov S K, Ptashkina-Girina O S, Nizamutdinova N S 2020 Principles of researching the energy potential of natural reservoirs in the power supply system Agroindustrial complex of Russia 27 (5) 821–28
[7] Segun A Giwa, Ali N, Ahmad I, Asif M, Guo R-B, Li F-L, Lu M 2020 Prospects of China’s biogas: Fundamental, challenges and considerations Energy Report 6 2973-87
[8] Scarlat N, Dallemand J F 2016 Technology Development Report Heat and Power from Biomass Low Carbon Energy Observatory Deliverable D 2.1. JRC102407
[9] Yang J, Chen B 2014 Energy analysis of a biogas-linked agricultural system in rural China- a case study in Congcheng Yao autonomous county Appl. Energy 118 (1) 173-82
[10] Bertsch N, Marro P 2015 Getting the Business Model Right Making Renewable Energy a success in Bangladesh
[11] Paolini V, Petracchini V, Segreto F, Tomassetti M, Naja L, Cecinato A N 2018 Environmental impact of biogas: A short review of current knowledge J. Environ. Sci. Health A 53 (10) 899-906
[12] Sheryazov S K 2008 The integrated power supply system using renewable sources research The KrasSAU bulletin 5 302-05
[13] Sheryazov S K, Doskenov A H 2019 The Increase of the Effectiveness of the System of Solar Heat Supply International Multi-Conference on Industrial Engineering and Modern Technologies (FarEastCon) 1-6 DOI: 10.1109/FarEastCon.2019.8934427
[14] Sheryazov S K, Ptashkina-Girina O S, Teljubaev Z B 2017 Recycling of animal waste for use as fertilizer The IrGSKhA bulletin 80 184-89
[15] Sheryazov S K, Vasenev V V, Teljubaev Z B 2016 Methods for increasing the efficiency of biomass processing in a biogas plant Materials LV scient. and tech. Conf. "Achievements of Science for Agroindustrial Production"(Chelyabinsk: SUSAU) pp. 230–35
[16] Sheryazov S K, Ptashkina-Girina O S, Nizamutdinova N S 2018 Technological and Economic Evaluation of the System of Heat Supply with the Usage of Renewable Sources of Energy International Multi-Conference on Industrial Engineering and Modern Technologies (FarEastCon) 1-5 DOI: 10.1109/FarEastCon.2018.8602526
[17] Sheryazov S K, Shelubaev M V 2010 Choosing a wind power plant Agricultural mechanization and electrification 2 7
[18] Sheryazov S K, Vasenev V V 2017 Analysis of the parameters of biogas plants The materials of the Int. Scient. and Tech. Conf. "Scientific and technical support of the agro-industrial complex of Siberia" (SIBIME SFSCA RAS - Novosibirsk) 2 137-41
[19] Vasenev V V, Teljubaev Z B 2017 To the choosing a biogas plant methodology Materials of the I All-Russian scient-practical conf. (Kurgan State Agricultural Academy) pp 118-21
[20] Sheryazov S K, Ptashkina-Girina O S, Teljubaev Z B 2021The Effluent Disinfection Based on the Cavitation Effect IOP Conference Series: Earth and Environmental Science 666 052077
[21] Sheryazov S K, Vasenev V V, Teljubaev Z B 2018 Optimization of Reactor Parameters in Anaerobic Digesters In the compendium: International Ural Conference on Green Energy (UralCon) 80-85 DOI: 10.1109/URALCON.2018.8544375
[22] Vasenev V V, Sheryazov S K 2018 Study of the parameters of biogas plants for processing animal waste The Orenburg State Agricultural University bulletin 3 (71) 169-172
[23] Vedenev A G, Maslov A N 2006 Construction of biogas plants A short guide-B.: "Euro" 28
[24] Isachenko V P, Ospitova V A, Sukomel A S 1975 Heat transmission A textbook for universities, (M "Energy") p 488
[25] Zemskov V I 2014 Renewable energy sources in the agro-industrial complex A study guide (SPb.: publishing house "Lan") pp 368