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BIOGAS PLANT WITH THE SYSTEM OF CIRCULATION CIRCUITS

The problems of thermal stabilization and mixing in a biogas plant (BGP) are analyzed, taking into account the features of vital activity of methanogenic bacteria. An air-lift method for organizing circulation in the system, which ensures uniform heat supply and mixing, is proposed and analyzed taking into account microbiological features of the anaerobic process.

Key word: *bioreactor, complex mixture, two-phase flows, high-viscosity liquids, air-lift method, biogas plant, thermal stabilization, energy efficiency.*

Introduction

Specific yield of biogas is influenced by the type of BGP process flowsheet, thermal stabilization quality, mixing method and intensity, carbon / nitrogen ratio, the substrate hydrogen index upstream of the reactor and in the reactor, presence of the process inhibitors, the substance turnover rate, etc. [1].

Stabilization of thermal modes in the biogas plant reactor is complicated by the necessity of taking into account microbiological features of anaerobic processes. Pressure drops have negative influence on the flow of bioconversion process and, therefore, it is necessary to combine heat supply for compensation of the bioreactor pressure losses with mixing the raw stock [2]. For supplying thermal energy to the substrate, internal and external recuperative heat-exchange devices are used as well as contact heat exchangers [3]. In certain cases, at the stage of a bioconversion system design heat-exchanging devices are expedient to be placed outside the reactor and, therefore, there is a necessity to install a pump for the substrate. In such case sensitivity of the bacterial medium to the motion speed should be taken into account. The substrate mixing at the speed exceeding 0.6 m / s reduces viability of methanogenic bacteria, which could reduce the biogas yield. In the pump such regions are formed, where linear velocities of the liquid could exceed 0.6 m / s. Under the conditions of pump operation it is difficult to control velocities in these regions of the circulation system.

For solving the problems of mixing and thermal stabilization in biogas plants, taking into account the substrate speed limitations ($W_s \leq 0{,}6$ m / s), there is a necessity to organize circulation without the use of a pump. Circulation can be organized using the air-lift method, which provides supplying a part of biogas from the reactor to the section downstream of the heat exchanger by means of a special pumping device. In this case it is possible to control the biogas supply to the attachment and in this way to set the pre-determined linear speed of the substrate.

The research aims at the development of a method for energy-efficient BGP design by combining rational processes of thermal stabilization and mixing through implementation of the circuits with a heat exchanger and an air-lift system of circulation organization.

Main part

The proposed circuit with an air-lift method for circulation organization operates in the following way (Fig. 1, a) [5]. Via supplying pipeline 2, the substrate is fed to shell-and-tube heat exchanger 3, where it is heated by water with the temperature t_w to the required temperature t_s. From reactor 1, the biogas is supplied by blower 4 to the heat exchanger upper attachment 5, where the heated substrate is supplied simultaneously. In the attachment a two-phase gas-liquid flow is created, the density of which is lower than that of the substrate. Due to the difference between the weights of the columns in the bioreactor and in the BGP thermal stabilization system, the substrate speed of $W_s \leq 0.6$ m / s could be provided for the same heights of the columns. In the attachment a riser section with a two-phase medium and the length L_{riser} is formed and a driving head P_{dr} is created in the system. The two-phase gas-liquid mixture is directed to separator 6 and after that the substrate returns to bioreactor 1 via pipe-line 7, while the biogas is discharged to gasholder 8.

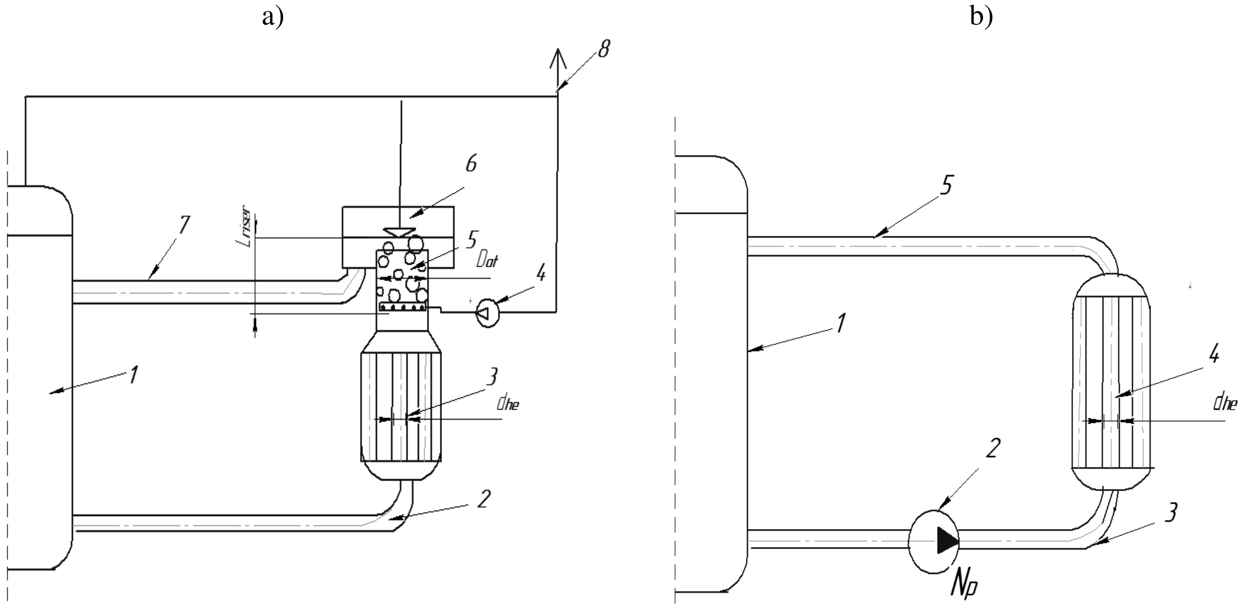

Fig. 1. a) Circulation circuit with a heat exchanger and a riser section:
1 – reactor, 2 – supply pipeline, 3 – heat exchanger, 4 – biogas blower, 5 – attachment with a riser section, 6 – separator, 7 – return pipeline, 8 – gasholder
b) Circulation circuit with a heat exchanger and a pump with electric motor:
1 – reactor, 2 – pump, 3 –supply pipeline, 4 – shell-and-tube heat exchanger, 5 – return pipeline

On our opinion, such system of circulation circuits (Fig. 1, a) can solve the problem of substrate mixing and supplying heat to compensate heat losses in the reactor [5]. To analyze energy efficiency of such system, it was compared to the system with a pump.

So, for numerical investigation of energy consumption the following variants of BGP thermal stabilization system are proposed:

1. The system with a heat exchanger and an attachment (riser section) with a biogas blower (Fig. 1 a);

2. The system with a heat exchanger and an electric motor for the pump (Fig. 1 b).

To analyze energy consumption of the given systems, mathematical models were used for:

1. determination of per day biogas yield from the bioreactor of a certain volume;

2. determination of the bioreactor heat losses into the environment;

3. thermal design of the circulation circuit with a heat exchanger and an air-lift riser section for the system with a pump;

4. hydraulic design of the circulation circuit with a heat exchanger and air-lift riser section for the system with a centrifugal pump;

5. determination of the biogas proportion for electric energy generation for driving the biogas blower and the pump.

To determine per day biogas yield from the bioreactor, operation of industrial biogas plants, produced by the following companies was analyzed: «Colorado-Biogas» (US), "ENBOM" (Finland), «Biosystem» (Sweden), "Pekenzheny-ring" (France), «Nichimen Corporation» (Japan), "Klauhen" (Denmark) [6]. In numerical research it was assumed that for the unit working volume of the reactor specific biogas yield is w=1 – 2,5 m^3 per day. Then per day biogas yield from the reactor of the volume V_r will be

$$W = w \cdot V_r. \qquad (1)$$

In this case biogas yield depends on observing the conditions, which enhance viability of the methane-producing bacteria. Due to the controlled biogas supply to the riser section of the reactor and definite design characteristics of the air-lift system, there is a possibility of adjusting the substrate speed at the level not exceeding 0.6 m / s in all components of the thermal stabilization system (in the supply and return pipelines, the heat exchanger pipes, in the attachment with a two-phase region).

Almost for all bioreactor volume values V_r=10...1000 m^3, taken for our research, thermal stabilization system with the air-lift method implementation consists of n circulation circuits with a heat exchanger. According to [7], the heat exchanger consists of n modules. Installation of such circulation circuits makes it possible to achieve uniform temperature distribution over the bioreactor, taking into account microbiological features of anaerobic fermentation process.

In order to determine the bioreactor heat losses and to perform thermal calculation of the module in the circuit with the air-lift attachment as well as for the circuit with the pump, mathematical models were built using the known heat balance and heat transfer equations [8]. The problem, arisen in mathematical modeling due to the difficulties of determining heat transfer intensity in complex mixtures, was solved with the application of experimental computation method (ECM) [9].

To elaborate the mathematical model for hydraulic calculation of the circuit with a heat exchanger and air-lift riser section, the procedure [10] was used, which was adapted to the operating conditions of the given circulation circuit. Balance equations of electromotive forces and hydraulic resistances as well as material balance equations, which form the basis of the given procedure, we refined due to special features of the circuit with a heat exchanger and air-lift device (the riser section).

In the circuit with the air-lift heat exchanger and the attachment, where there are single-phase and a two-phase regions, the balance equation of electromotive forces and hydraulic resistances has the following form (Pa):

$$P_{ef} = \sum \Delta P_l, \qquad (2)$$

where P_{ef} – effective head; $\Sigma\Delta P_l$ – total pressure losses at single-phase sections .

For single-phase regions of the circuit (the supply and return pipelines, the heat exchanger pipes) the material balance equation has the following form (kg / s):

$$G' = \rho' \cdot W'_{0i} \cdot \omega_i = const. \qquad (3)$$

In the two-phase region of the circuit (riser section downstream of the heat exchanger), kg / s:

$$G_s{}' = \rho' \cdot W'_0 \cdot \omega_{two-ph} + \rho'' \cdot W''_0 \cdot \omega_{two-ph} = const, \qquad (4)$$

where G', G'_s – mass flow rates of the substrate and gas-liquid mixture (substrate + biogas); ρ', ρ'' – substrate and biogas densities; $W_0{}'$, $W_0{}''$ – superficial velocities of substrate and biogas respectively; ω_i – the area of i-th effective cross-sections of the single-phase regions; $\omega_{two\text{-}ph}$ – effective cross-sectional area of the two-phase regions (of the cylindrical attachment).

Net effective head P_{ef}, Pa, is determined by

$$P_{ef} = P_{dr} - \Delta P_t^{two-ph}, \qquad (5)$$

where P_{dr} – driving head; $\Delta P_t^{two\text{-}ph}$ – total pressure losses at the two-phase region in the heat exchanger attachment, Pa:

$$\Delta P_t^{two-ph} = \Delta P_f^{two-ph} + \Delta P_{ac}^{two-ph} + \Delta P_w^{two-ph}, \qquad (6)$$

where $\Delta P_f{}^{two\text{-}ph}$, $\Delta P_{ac}{}^{two\text{-}ph}$, $\Delta P_w{}^{two\text{-}ph}$ – pressure losses for friction, acceleration and weight pressure losses.

In the computation of hydrodynamic processes in the circuit there were problems due to uncertainty of thermal-physical properties (TPP) of the substrate as well as in the computation of pressure loss components in the two-phase vertical flow of highly viscous liquid.

To provide closure of the mathematical model, TPP of the substrate were estimated using ECM.

The energy conservation equation served as a basis for determining components of the pressure drop in the two-phase high-viscosity flow. Pressure losses for friction at the two-phase region were determined using the equation for high-viscosity liquids under low pressure conditions [11]:

$$\Delta P_f^{\,two-ph} = \Delta P_{f1} \cdot \left[1 + \Psi \cdot \left(\frac{W_0^{''}}{W_0^{'}} \right) \right], \tag{7}$$

where ΔP_{f1} – pressure losses in the single-phase flow, Pa; Ψ – correction for the two-phase flow, which is determined by the criterial equation for high-viscosity two-phase flows and is a function of dimensionless defining parameters of the two-phase flow.

Correction Ψ is determined according to [11]:

$$\Psi = 91{,}6 \cdot Fr_0^{-0{,}26} \cdot Fr_{ci}^{\;-0{,}43} \cdot \left(\frac{\rho_2}{\rho_1} \right)^{0{,}15} \cdot \left(\frac{\mu_1}{\mu_2} \right)^{-0{,}12} \cdot Re_1^{-0{,}08}, \tag{8}$$

where μ_1, μ_2 – dynamic viscosities of the liquid and gaseous phases; ρ_1, ρ_2 – densities of the liquid and gaseous phases; Froude criterion of the mixture $Fr_m = W_m/(g \cdot D)$; Froude criterion $Fr_0 = W_0/(g \cdot D)$; Reynolds criterion for liquids $Re_1 = (W_0^{'} \cdot D)/\nu_1$; W_m, W_0, $W_0^{'}$– the velocity of two-phase mixture, circulation rate and superficial velocity of the liquid, D – diameter of the pipe with the two-phase region, g – gravitational acceleration, ν_1 – kinematic viscosity of the liquid.

Mathematical model for hydraulic design of the circulation circuit with the pump for the case, when there are only single-phase pipeline regions in the system, was built on the basis of the known dependencies for calculation of the total pressure losses and the substrate flow rate in the circuit. To solve the substrate TPP uncertainty problem, ECM procedure was used [9].

Mathematical model for determining the proportion of biogas, required for electricity generation to drive the biogas blower and the pump, comprises dependencies for electric power consumption to drive the biogas blower and the pump and other known equations [13, 14], presented below in Table 1.

Research results

For realization of the mathematical models, which were used in this research, we considered a definite example with the following initial data: the reactor volume V_r=10...1000 m^3; the substrate temperature in the reactor t_r=35 °C; ambient temperature t_{amb}=4 C; the heating water temperature t_w=47 °C; the liquid – substrate humidity 92%; to determine coefficient α_1 of the heat transfer to the substrate, ECM was used; coefficient of heat transfer to the air α_2=23W/(m^2·K); coefficient of heat transfer to the heating water was determined by the known procedures [8]; thermal conductivity of steel λ_{st}=45 W/(m·K); thermal conductivity of the insulation λ_{ins}= 0,035 W/(m·K); thickness of the reactor wall δ_w=35 mm; thickness of the insulation δ_{ins}=500 mm.

Basic dependencies for assessing and comparing energy efficiency of the system with the biogas blower and the system with the pump for the substrate are given in Table 1.

Table 1

Estimation of the biogas proportion for electric energy generation to organize circulation in the system of BGP circuits

Indicators of circulation organization № n/n	Biogas blower in the circulation system with the heat exchanger and air-lift	The substrate transfer pump in the circulation system with the heat exchanger
1.	$N_{gb} = \frac{Q'' \cdot P}{1000 \cdot \eta_{bl} \cdot \eta_{mech}}$	$N_{sp} = \frac{Q' \cdot P}{1000 \cdot \eta_{sp} \cdot \eta_{mech}}$
2.	$Q_{el}^{bl} = N_{gb} \cdot 24$	$Q_{el}^{sp} = N_{sp} \cdot 24$
3.	$Q_{me}^{bl} = \left(Q_{el}^{bl} \cdot 3600\right) / \eta_{cps}$	$Q_{he}^{sp} = \left(Q_{el}^{sp} \cdot 3600\right) / \eta_{cps}$
4.	$V_{bg}^{bl} = Q_{he}^{bl} / Q_l^o$	$V_{бг}^{sp} = Q_{he}^{sp} / Q_l^o$
5.	$\chi_{bl} = V_{bg}^{bl} / W$	$\chi_{sp} = V_{bg}^{sp} / W$
Notes to the equations	Q'' – volumetric flow rate of biogas, m^3/s; P– biogas pressure in the attachment, Pa; η_{bl}– efficiency of the blower (η_{bl}=0,6…0,75) [12], values adopted in the calculations: η_{bl}=0,69; η_{mech} – mechanical efficiency (η_n=0,96) [13]; η_{cps}=0,38 – efficiency of the condensing power station [15]	Q'– volumetric flow rate of the substrate, m^3/s; P – pressure losses in the circuit, Pa; η_{sp}– efficiency of the substrate transfer pump (η_{sp}=0,49…0,6), values adopted in the calculations: η_{sp}=0,55 [14]; Q_l^o – biogas lower heating value, Q_l^o=22000 kJ / Nмм^3.

Table 1 (1 -5) gives the following indicators of circulation organization for the system with biogas blower, heat exchanger and air-lift as well as for the system with the substrate transfer pump:

1. Power at the blower shaft, kW

Per day electric energy consumption for the electric motor, kWh

2. The amount of heat energy, required for per day electric energy generation at the condensing station, according to item 2, kJ
3. Per day biogas consumption for heat generation, Q_{he}^{bl} and Q_{he}^{pm}, Nm^3
4. Proportions in the amount of BGP-produced biogas, which are consumed to generate electricity for biogas blower and for the substrate transfer pump respectively.

Application of the mathematical models, described in the main part, has made it possible to determine the following indicators:

- the bioreactor heat losses into the environment, depending on the bioreactor volume Q_l = 384...1062 W;
- the required number of circulation circuits, depending on the volume of the reactor with the modules n_c=1...14;
- basic design parameters of the heat-exchanging module: diameter of the heat exchanger pipes d_{he}=50 mm; length of the pipes L_p=1700 mm; the attachment diameter D_a=120 mm; the supply line diameter d_1=106 mm; the return line diameter d_2=106 mm; the supply pipeline length l_2=1700 mm; the return pipeline length l_2=2000 mm; the attachment height L_a=350 mm;
- electric power of the biogas blower N_{bl}=4,69...65,7 W; electric power of the centrifugal pump motor N_{sp}=6,9 ... 96 W;
- the proportion of the produced biogas, which is consumed to generate electric energy for the electric motor of the biogas blower for w = 1 m^3–χ=0,6 ... 0,09%; proportion of biogas consumed to generate electricity for the pump motor for w=2,5 m^3 per day – χ=0,24...0,03%; biogas proportion, spent to generate electricity for the pump motor for w=1 m^3 per day – χ=0,9...0,12%; biogas proportion, spent to generate electricity for the pump motor for w=2,5 m^3 per day – χ = 0,36 ... 0,05%.

Dependence of the biogas for electric energy generation χ on the bioreactor volume V_r is presented graphically in Fig. 2:

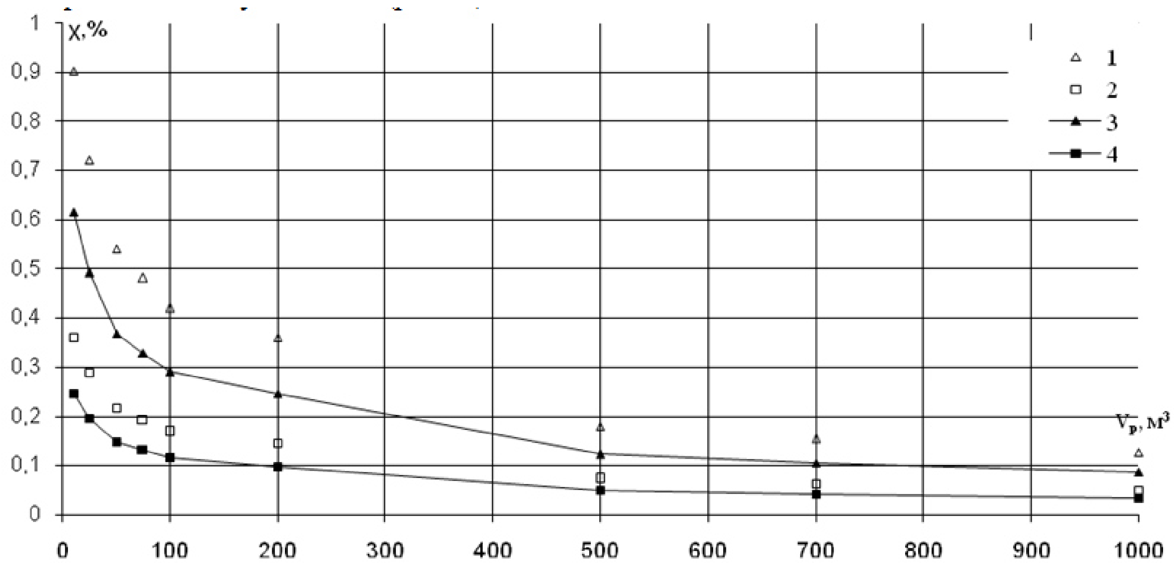

Fig. 2. 1 – biogas blower for *w=1* m^3 per day; 2 – biogas blower for *w*=2,5 m^3 per day; 3 – pump for *w =1* m^3 per day; 4 – pump for *w*=2.5 m^3 per day

The comparative analysis of the air-lift system and the system with a pump (Fig. 2) has shown that in the case of biogas blower application the proportion of biogas will be by 1.5 – 1.4 times smaller than that in the case, when circuit with a pump is used. In terms of energy consumption, the air-lift system is more efficient and, besides, it takes into account microbiological features of the anaerobic process, namely, the substrate velocity limitations ($W_s \leq 0.6$ m / s). This facilitates the increased yield of biogas.

A single biogas blower could be installed for all circulation loops of BGP, while in the case of the system with the substrate transfer pump, biogas blowers should be installed in each circulation loop. Small blowers for such abrasive mixtures as the substrate have low efficiency, while the efficiency of biogas blowers is higher [13, 14].

Another advantage of the system of circuits with the air-lift attachment and biogas blower, as compared to the system with a pump, is absence of the contact of the equipment movable elements with the substrate. If system with a pump is used, the substrate pumping leads to rapid wearing of the pump components.

Conclusions

A system with the air-lift method for circulation organization is proposed. It combines the thermal stabilization and mixing processes in BGP and makes it possible to take into account microbiological features of the process. This system is compared with the system that includes a heat exchanger and a pump.

In order to analyze energy consumption of both systems, mathematical models were used to determine the following indicators: heat losses in the bioreactor; heat exchange intensity in complex mixtures with uncertain rheological and thermophysical properties; characteristics of two-phase flows – complex mixture + biogas; the number of heat-exchanging modules; electric power of electric motors of the biogas blower and the substrate transfer pumps; the proportion of biogas consumed to generate electric energy for the biogas blower and for the pumps in the circulation circuit.

As a result of research it was determined that electric energy consumption for the system with a biogas blower is 40 – 50 % less than that for the system with pumps. In addition, the following advantages of the air – lift system of circulation organization were found:

1. The possibility of taking into account the substrate velocity limitations in all the sections of the circuit (W_s≤0,6 m / s) by adjusting the biogas supply to the attachment;
2. Absence of the direct contact of the movable elements with the substrate;
3. The possibility to install a single biogas blower for all circulation circuits of the bioreactor.

The research results are recommended for further feasibility analysis as to implementation of vertical circulation circuits with the air-lift method for circulation organization into the practice of creating energy efficient environment-friendly BGP.

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