Define of effective process working combine mixing system

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Abstract. Biogas technologies as an alternative energy source are widespread in the EU countries. But on the territory of the Russian Federation, this process is poorly understood. Since the potential from the use of biogas technologies is significant, a combined substrate mixing system has been proposed. Computer simulation of various mixing parameters was carried out and optimal modes were determined. As a result of a series of computational experiments, it was found that the developed mixing system allows the mixing time to be doubled in comparison with the traditional mechanical mixing system in a cylindrical bioreactor. At the same time, the uniformity of mixing is 16% higher. The volume of stagnant zones is 2.72 times lower. The obtained results give grounds to assume about a possible improvement of the habitat for microorganisms and, as a consequence, an increase in the rate of their distribution in the bioreactor, which in turn increases the rate of fermentation and the volume of biogas produced.

1. Introduction

In developed countries, anaerobic processing of organic waste is actively used to obtain an alternative source of energy - biogas.

Anaerobic digestion of organic waste helps to reduce heavy reliance on fossil fuels for energy needs, removes unwanted odor compounds and reduces pathogens in waste.

There are several lines of research to improve the efficiency of biogas production. Among the main directions is:
- increase in the temperature of the fermentation process;
- creation of strains of highly active microorganisms;
- the use of anaerobic biofilters for the immobilization of methane-forming bacteria;
- intensification of heat and mass transfer using a mixing system.

Within a certain temperature regime, the issue of increasing the intensity of biogas production largely depends on the method of mixing the biomass [1], since mixing ensures constant contact of microflora with the nutrient medium and untreated sludge. The resulting sludge contains up to 60-80% of organic matter, of which only part passes into biogas.

There are three fundamentally different mixing methods: mechanical, pneumatic, hydraulic [2].

The most important characteristics of a mixing device are mixing intensity and mixing efficiency.

Determination of mixing efficiency depends on the purpose of mixing and expresses the quality of the mixing process. An indicator of the qualitative mixing in the digester is the degree of homogeneity of the biomass in terms of the concentration of organic matter and temperature throughout the digester volume [3, 4]. In this case, excessive mixing can disrupt the consortium of microorganisms and thereby disrupt the fermentation process.
When determining the intensity of mixing, the following indicators are used: the number of revolutions of the mixer, the peripheral speed of the mixer blade, the modified Reynolds number, the specific power, the homogenization time, the pumping capacity of the mixer, the circulation capacity of the mixer, the coefficient of turbulent mixing. Moreover, each of the indicators is applied from the type of process [5].

In biogas plants, the mixing intensity limits the mass transfer between the cell and the culture medium [6] and depends on the time to achieve a given technological result or, for mechanical mixing, the number of revolutions of the mixer [3]. In bubbling mixing systems, the mixing intensity depends on the flow rate of the bubbling gas, namely, on the distance between the bubbles horizontally and vertically, and the smaller it is, the more active the mixing process will be in the tank [2, 7]. As a quantitative indicator of the intensity of mixing, the value of the ratio \( \frac{I(t)}{t} \), where \( t \) – mixing time [2].

In the works of the author Karmin, it was determined that agitation with gas was shown to be more effective than mechanical [8].

Later Varma and Al-Dahhan (2007) used the technique and configuration of the digester proposed by Karmin to compare the hydrodynamic performance with the two types of barborators, and concluded that an evenly distributed multi-hole barborator is better than a single-hole barborator for mixing gases in the digester.

With the introduction of computational fluid dynamics (CFD), several researchers have conducted CFD-based simulations of gas mixing in anaerobic digesters. Vesvikar and Al-Dahhan used CFX software to simulate gas mixing in a laboratory digester, in which slurry containing 5% solids was considered water. The results of modeling with a single point bubbler showed that the speed of the cfd and cfx modeling of mixing in anaerobic reactors are also reflected in the following works of foreign researchers gas flow, the height of the chimney and the shape of the bottom of the digester insignificantly affect the characteristics of the flow, however an increase in the chimney diameter leads to an increase in the velocities of the liquid phase outside the tube. Karim et al. (2007) used the finite element method to solve the problem of gas mixing inside a gas lift digester and compared flow patterns with and without a suspended baffle. In their model, sewage sludge was considered as a non-Newtonian power-law fluid, but the effects of turbulence were not considered. In addition, the effect of the gas phase has been simplified by specifying the velocity at the outlet of the tube. In fact, this model can only be viewed as a single phase model. It is interesting to note that the simulation results based on the above simplification fit well with their two-phase flow measurements.

The issues of cfd and cfx modeling of mixing in anaerobic reactors are also reflected in the following works of foreign researchers [8–12].

2. Materials and methods

Gas agitation in anaerobic reactors is a complex multiphase and turbulent flow that is determined by conservation of mass and momentum, turbulence transfer, and interphase momentum transfer. Thus, when developing a theoretical model that characterizes the mixing process, the following assumptions were made:

- The fermentation temperature is constant at 35 °C and each phase is an isothermal and incompressible liquid;
- It is assumed that the two-phase flow is a bubble flow in which liquid manure is treated as the primary phase and gas as the second phase;
- The liquid phase can be water or a non-Newtonian pseudoplastic liquid, which depends on TS (solids content);
- Different phases move at different speeds (slip speeds);
- The drag force from the liquid phase acting on the gas bubbles enters the interphase exchange of impulses;
- There is no external force of the body and no force of virtual mass, and the influence of the lift force on the bubbles is insignificant;
Self-mixing under the action of natural biogas and heat convection flows caused by the addition of heat is negligible. The mixing process in the digester was simulated using fluent 19.3. Water is taken as a mixing medium. Bubbling gas - CH₄. The turbulization model is a standard k-ε model, since it has a minimum error when modeling a two-phase flow of a medium [8] at TS = 0%.

To determine the optimal operating mode of the combined mixing system, a computer model of the digester with dimensions of 1.0 - 1.0 - 1.0 m was used. The search for the optimal mode of mixing the biomass was carried out by changing two factors: the shaft rotation speed and the flow rate of the bubbling gas. In this connection, it becomes possible to use a two-factor experimental design.

The optimal speed of rotation of the shaft and the flow rate of the bubbling gas were taken on the basis of the recommended parameters of the vital activity of microorganisms, as well as on the basis of the recommendations of the intensity of mixing in digesters [13-15].

The shaft rotation speed was - 25 rpm.

Gas consumption from the mixing device – 0.0352 kg/sec.

Hole diameter 15 mm. Number of holes – 16.

There are the following methods for determining the quality of mixing: the use of dyes, the use of electrical conductivity, the use of the heat of solution, the use of a density difference, the use of a temperature gradient.

To assess the quality of the mixing system, we will use the temperature gradient method, which allows us not to complicate the computer model by three-phase modeling [5].

The method consists in determining the mixing time required to equalize the temperature of the liquid after a known amount of liquid with a higher temperature has been added to any part of the digester. The duration of stirring is determined by the time interval from the moment the temperature gradient is created until the temperature is equalized. The intensity of the heat impulse must be so high that the greatest temperature gradient is obtained during the operation of the apparatus [5].

To determine the mixing efficiency of the current model of the digester, the boundary conditions were taken as:

- Initial fluid temperature – 273K.
- At the bottom of the digester there is a layer of superheated water = 0.2 m is 373K.
- Sparged gas temperature – 273K.
- Heat transfer through the walls of the digester - adiabatic wall.
- Wall surface - sliding
The criteria for evaluating the efficiency were identified to determine the optimal mixing mode[16-17]:
1. Uniformity of the velocity field in the digester volume, % (y1). Determined by the ratio of the total volume of the substrate with uniform velocity fields to the total volume of the substrate.

\[ y_1 = \frac{\sum_{i=1}^{n} V_{en,i} V_{en}}{V_{total}} \]  

(1)

2. Average speed of movement of the substrate, m / s (y2). Determined by values in velocity fields.

\[ y_2 = v_{ave} \]  

(2)

3. The volume fraction of stagnant zones in the digester, % (y3). It is determined by the ratio of the volume of zones with a hydrodynamic regime that does not provide an effective mode of fermentation, in which the mixing rate is close or equal to zero.

\[ y_3 = \frac{V_{stag}}{V_{total}} \]  

(3)

3. Results and discussion
The experimental results of CFD computer modeling combine system illustrated in table 1.

| No. exp | Shaft rotation speed, rpm | Gas consumption at the outlet from the holes, kg/s | Uniformity of the velocity field, y1, % | Mixing speed of the substrate H2, m/s | Volume fraction of stagnant zones, y3, % | Volume at the rate of stirring the substrate, % | Time to complete mixing, sec |
|---------|---------------------------|---------------------------------------------|----------------------------------------|--------------------------------------|------------------------------------------|-----------------------------------------------|------------------------------|
| 1       | 10                        | 0.0009                                      | 89.8                                   | 0.13                                 | 11.9                                     | 63.9                                          | 35.9                          | 0.1                          | 13.4                        |
| 2       | 40                        | 0.0009                                      | 77.8                                   | 0.22                                 | 12.2                                     | 25.1                                          | 74.1                          | 0.8                          | 8.4                         |
| 3       | 10                        | 0.0036                                      | 94.1                                   | 0.24                                 | 27.6                                     | 37.7                                          | 55.5                          | 6.8                          | 8.0                         |
| 4       | 40                        | 0.0036                                      | 91.2                                   | 0.26                                 | 13.7                                     | 24.7                                          | 68.9                          | 6.1                          | 10.4                        |
| 5       | 25                        | 0.0022                                      | 93.1                                   | 0.20                                 | 11.0                                     | 35.4                                          | 61.9                          | 2.8                          | 8.4                         |
| 6       | 25                        | -                                          | 78.3                                   | 0.39                                 | 29.9                                     | 52.1                                          | 47.9                          | 0.0                          | 16.1                        |

The data obtained show that the fastest way to achieve uniform mixing is experiment No. 3, since the time to achieve complete mixing is 8 seconds. In this case, the axial movement of fluid currents along the shaft prevails, due to the increased flow rate of the bubbling gas. At the same time, this type of mixing forms the largest volume of stagnant zones.

The closest in terms of stirring speed to experiment No. 3 are experiments No. 2 and No. 5. At the same time, in experiment No. 2, a sharp gradient of speeds prevails in the volume of the container. What negatively affects the development of microorganisms in the digester.

The most optimal is experiment No. 5, where the time to achieve uniform mixing was 8.4 seconds, but the volume of stagnant zones and the uniformity of the velocity field significantly differ in a direction favorable for microorganisms.
Figure 2 for each experiment shows a graph of the volume of the stirred medium in the digester in a certain range of speeds.

![Graph showing volume of stirred medium in different mixing speeds](image)

**Figure 2.** Speed mixing in tank value.

Figure 3 shows the results of modeling the speed of movement of the stirred medium for each experiment. Lower limit = 0 m/s, upper = 1 m/s.

![Speed field images](image)

**Figure 3.** Speed field: a – experiments No. 1, b – experiments No. 2, c – experiments No. 3, d – experiments No. 4, e – experiments No. 5, f – experiments No. 6.

In experiment No. 1 (Figure 3, a), the shaft rotation speed is 10 rpm, the gas flow rate at the outlet from the holes is 0.0009 kg/s. In experiment No. 2 (Figure 3, b), the shaft rotation speed is 40 rpm, the gas flow rate at the outlet from the holes is 0.0009 kg/s.

Due to the more intense tangential movement of the liquid, the rising gas jet is compressed into a common flow, which in turn increases the rate of rise of the stirred medium, but at the same time reduces the entraining volume. Also, as a result of the increased speed of rotation of the blades in the
lower part of the digester, more intensive mixing occurs, which is clearly seen in Figure 3, b, experiment No. 2. The average mixing speed in the digester is 41\% higher and amounts to 0.22 m/s.

In experiment No. 3 (Figure 3, c), the shaft rotation speed is 10 rpm, the gas consumption at the outlet from the holes is 0.0036 kg/s. In experiment No. 4 (Figure 3, d), the shaft rotation speed is 40 rpm, the gas flow rate at the outlet from the holes is 0.0036 kg/s. In experiment No. 5 (Figure 3, e), the shaft rotation speed is 25 rpm, the gas flow rate at the outlet from the holes is 0.0022 kg/s.

Experience No. 3 in comparison with experiment No. 1 clearly shows that an increase in the flow rate of the bubbling gas leads not only to an increase in the average velocity of the profile, but also to the compression of the gas flow to the center of the reactor, which in turn makes the mixing in the digester less distributed, with the predominance of the axial mixing speed. As a consequence, there is an increase in the share of stagnant zones, in the current case by 15.7\%.

Experience No. 4 is the most intense and most energy-consuming, while about a third of the stirred biomass in the digester moves at a speed higher than the recommended 0.6 m/s, which also limits the rate of reproduction of microorganisms. Experience No. 5 is close to experiment No. 4 in terms of the provided distribution of the velocity profile, but it was found that 90\% of the mixed biomass moves with an allowable speed of up to 0.6 m/s. In experiment No. 6 (Figure 3, f), the shaft rotation speed is 25 rpm, the gas consumption at the outlet from the holes is absent.

This experiment was carried out to compare a combined mixing system and a mechanical one. As can be seen from the results, when using only mechanical stirring, twice the amount of time is needed to achieve complete mixing, while there is an increased uneven mixing – 78.3\% and an increased volume of stagnant zones – 30\%.

4. Summary
As a result of the simulation, the optimal shaft rotation speed and gas flow rate at the outlet from the holes were determined, namely: rotation speed - 25 rpm; gas consumption - 0.0022 kg / s. The obtained technical parameters were used as optimal for carrying out field experimental studies.

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