

Investigation of the effect of mixing and biomass temperature in the anaerobic digester on the volume of biomethane

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Abstract. The article is devoted to the study of the process of biomethane production during anaerobic fermentation in a biomethane installation. The most effective methods for increasing the efficiency of biomethane plants are to increase the intensity of mixing and the temperature of the biomass. However, currently there are various data on the optimal temperature of the fermentation process and the frequency of mixing of biomass per day. A program for conducting experimental studies and an experimental setup for producing biomethane with a bubble-type mixing system has been developed. For research, the central composite rotatable plan of the full factorial experiment was used. Experimental studies of the process of biomethane production during anaerobic fermentation of pig manure in mesophilic temperature conditions were carried out. In the process of implementing the plan, a regression equation was obtained that characterizes the effect of the bubbling mixing intensity and biomass temperature on the biomethane output. Plots of the dependence of the specific yield of biomethane on varied factors are obtained. A rational mode of operation of the biomethane plant has been established, which is achieved with a mixing intensity of 5...6 days⁻¹ and a biomass temperature of 39.5...40.5 °C with a maximum specific yield of biomethane of 393.58 l/kg. This mode can be recommended for the operation of biomethane plants in the processing of organic waste from agricultural enterprises.

1. Introduction

One of the promising areas for the development of alternative energy, which is widely used in the European Union (EU) countries, is biogas [1-3]. The difference of biogas from the natural one consists in low methane (40-70%) content and the presence of impurities such as: carbon dioxide (30-40%), hydrogen sulfide (0-2%) and other gases (0-5%). After purification, biogas is similar in chemical composition to natural gas and is called biomethane [4-6]. Biomethane is produced by biomethane units in the process of anaerobic fermentation of organic substances. Energy plants and agricultural wastes are used as an initial substrate for biomethane production [7-9].

To increase the intensity of the fermentation process, the following methods are used:

- the addition of various substances in the anaerobic digester, promoting the growth of bacteria;
- the retention of bacteria in the anaerobic digester using anaerobic biofilter;
- intensification of heat and mass transfer using mixing systems;
- increase in process temperature.

The most effective methods to increase the efficiency of the anaerobic digester are to increase the intensity of mixing and increase the temperature.



Modern biomethane installations operate under two temperature conditions: mesophilic (30–45 °C) and thermophilic (50–60 °C). Most existing biomethane plants operate in the mesophilic mode [10–12]. This allows you to get a large amount of biomethane at low energy costs for heating the anaerobic digester. However, there are various data on the optimal temperature of the anaerobic fermentation process in the mesophilic mode. In the earliest works [13–17], it is indicated that the greatest amount of biogas is released at temperatures of 32–35 °C. The authors of [18, 19] write that the optimum temperature is 36–37 °C. According to modern data, the optimal temperature range is 38–42 °C [20–22].

For uniform distribution of the biomass temperature and the concentration of bacteria throughout the methane tank, 3 types of mixing systems are used [23–25]: mechanical, hydraulic and bubble (pneumatic). The most widely used are mechanical systems with paddle and propeller mixers. Hydraulic mixing is carried out by recirculation of biomass from one part of the digester to another using a pump. Bubbling mixing is carried out by supplying biogas to the lower part of biomethane. Bubbles of gas rising upward cause the circulation of biomass and its intense mixing.

There are also conflicting data on the mixing frequency. In [7, 17–20] it is indicated that the ideal mode of mixing of the substrate is several times a day (4–12 days⁻¹). In large-volume anaerobic digesters, mechanical stirrers of continuous or quasi-continuous operation are mainly used [22–25].

The aim of this work is to study the effect of bubbling mixing intensity and biomass temperature in the anaerobic digester on the efficiency of the fermentation process.

2. Materials and Methods

To conduct experimental research, an experimental setup was developed (Figure 1) [26]. The installation consists of a anaerobic digester, in which fermentation takes place, a gasholder for collecting biomethane, devices for heating and mixing biomass and instrumentation.

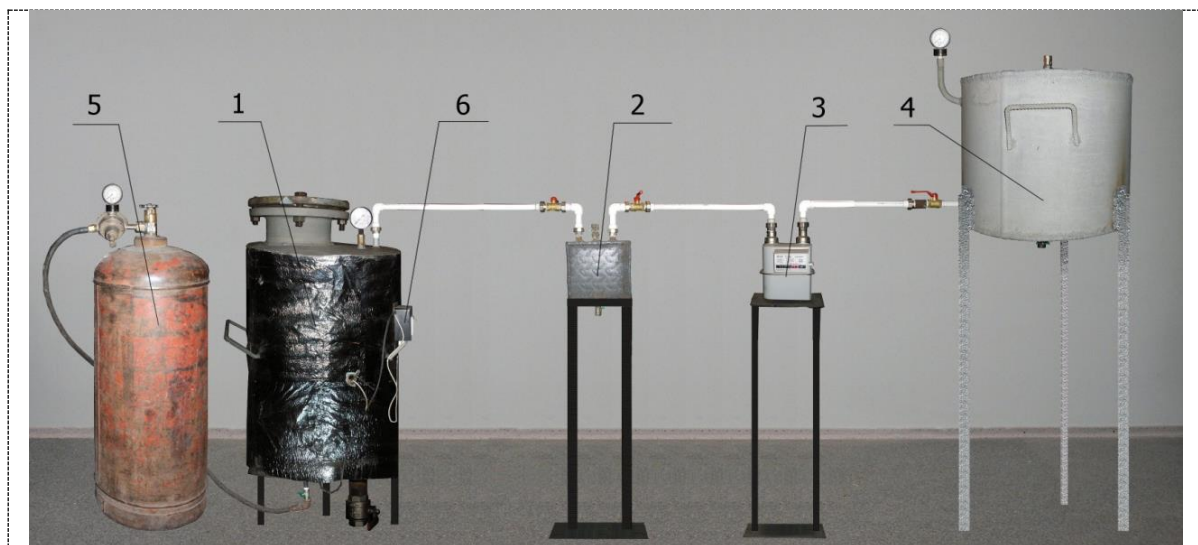


Figure 1. General view of the experimental setup for biomethane production: 1 – anaerobic digester, 2 – hydraulic shutter, 3 – gas meter, 4 – gas tank, 5 – gas bottle.

In the experimental setup, a bubbler type anaerobic digester is used, the distinguishing feature of which is the design of the mixing system (Figure 2). The bubbler mixing device is a uniformly perforated pipe in the form of a vertical spiral, the turns of which form a cone. The anaerobic digester also contains a pipe for supplying the initial substrate, a pipe for draining biomass, a pipe for removing the resulting biomethane.



Figure 2. The anaerobic digester with system of hashing of bubbling type.

The heating device of the anaerobic digester is a thermocouple in the form of a cord, evenly located outside the anaerobic digester shell. This position of the thermocouple allows you to make the heating uniform and ensure the temperature regime within the specified limits. The automation system of the experimental setup maintains a predetermined temperature in the anaerobic digester constant.

The principle of operation of the installation is as follows. The prepared initial substrate is fed into the anaerobic digester 1 through the inlet pipe, after filling the anaerobic digester is hermetically closed. Using a heating device 6, the biomass is heated to the desired temperature and maintained at a given level. In the fermentation process, biomethane is released, which is collected in the upper part of the anaerobic digester and through the connecting pipelines, passing through the hydraulic shutter 2 and gas meter 3, enters the gas tank 4 for further consumption. From the gas bottle 5, the gas of the required pressure is supplied to the bubbler mixing device installed in the lower part of the anaerobic digester.

Pig manure with a volumetric humidity of 90% was used as the initial substrate. The temperature regime is mesophilic. The cycle time of the biomethane production process was 30 days.

When conducting experimental studies, the following parameters were subject to direct measurement:

- volumetric flow rate of biomethane;
- temperature in the anaerobic digester;
- pressure in a anaerobic digester, gas tank and gas bottle.

The main indicator of the experimental study is the specific yield of biomethane V (l/kg), determined in liters per kilogram of dry matter:

$$V = V_B/m, \quad (1)$$

where V_B – the volume of biomethane produced, l; m – the mass of absolutely dry biomass matter in the anaerobic digester, kg.

The volumetric flow rate of biomethane was determined using a VK – G1.6T gas volumetric meter. Since the volume of gas used for mixing also passes through this counter, the volume of biogas produced is determined as the difference between the counter readings on the gas holder (V_2) and the counter installed on the cylinder (V_1), which supplies gas to bubble mixing:

$$V_B = V_2 - V_1 \quad (2)$$

The substrate temperature in the anaerobic digester was measured with a thermometer of the technical grade TTZh-M. To control the pressure in the gas tank, anaerobic digester, and bubbler mixing system, pressure gauges DM 02-100-2-M are used.

The experimental research program provides for the determination of the effect of bubbling mixing and substrate temperature in the anaerobic digester on the fermentation process and the release of bi-

omethane. The specific yield of biomethane is taken as the optimization parameter, then the response function has the form:

$$V = f(t, \eta), \quad (3)$$

t – biomass temperature in anaerobic digester, °C; η – mixing frequency, day⁻¹.

For conducting experimental research, we will use the methods of matrix design of experiments, which allows us to reduce the number of experiments.

Taking into account the coding of the studied factors, the response function has the form:

$$V = f(X_1, X_2), \quad (4)$$

X_1 – biomass temperature in anaerobic digester, °C; X_2 – mixing frequency, day⁻¹.

For research, we use the central composite rotatable plan for the full factorial experiment (CCRP FFE). Application of such a plan allows to reduce the number of experiments to a minimum and to obtain the regression equation in the form of a second-order polynomial.

The matrix of the central compositional rotatable plan is based on the full factorial experiment – 2^n , where n – the number of variable variables (in our case $n = 2$), with the addition of $2n$ stellar points at the $\pm\alpha$ level and 5 zero points (N_0). The total number of experiments according to plan for $n = 2$ will be:

$$N = 2^n + 2n + N_0 = 13 \quad (5)$$

The values of the levels of factors on a conditional scale are set as follows: maximum +1, average 0 minimum –1 and “star” points +1.41, –1.41.

Based on the foregoing, a second-order rotatable plan matrix has been compiled for CCRP FFE 2^2 for two independent variables – the frequency of mixing of the biomass and the temperature of the biomass (Table 1).

Table 1. Planning matrix CCRP FFE 2^2

Experience number	Experience number X_1	X_2	Target function V (l/kg)
1	–1	–1	223
2	+1	–1	265
3	+1	+1	279
4	–1	+1	232
5	+1.41	0	412
6	–1.41	0	65
7	0	+1.41	260
8	0	1.41	124
9	0	0	199
10	0	0	205
11	0	0	189
12	0	0	192
13	0	0	207

The values of all factors required by the central compositional rotatable plan of the full factorial experiment according to the selected scheme are given in Table 2.

Table 2. Factor Variation Levels

Factors	Variation interval	Factor Variation Levels				
		-1.41	-1	0	+1	+1.41
X_1 – biomass temperature in anaerobic digester (°C)	2.5	33.5	34.5	37	39.5	40.5
X_2 – mixing frequency (day ⁻¹)	2	0	1	3	5	6

3. Results and Discussion

The results of a multivariate experiment of the function $V = f(\eta, t_i)$ are presented in the form of a regression equation in physical quantities:

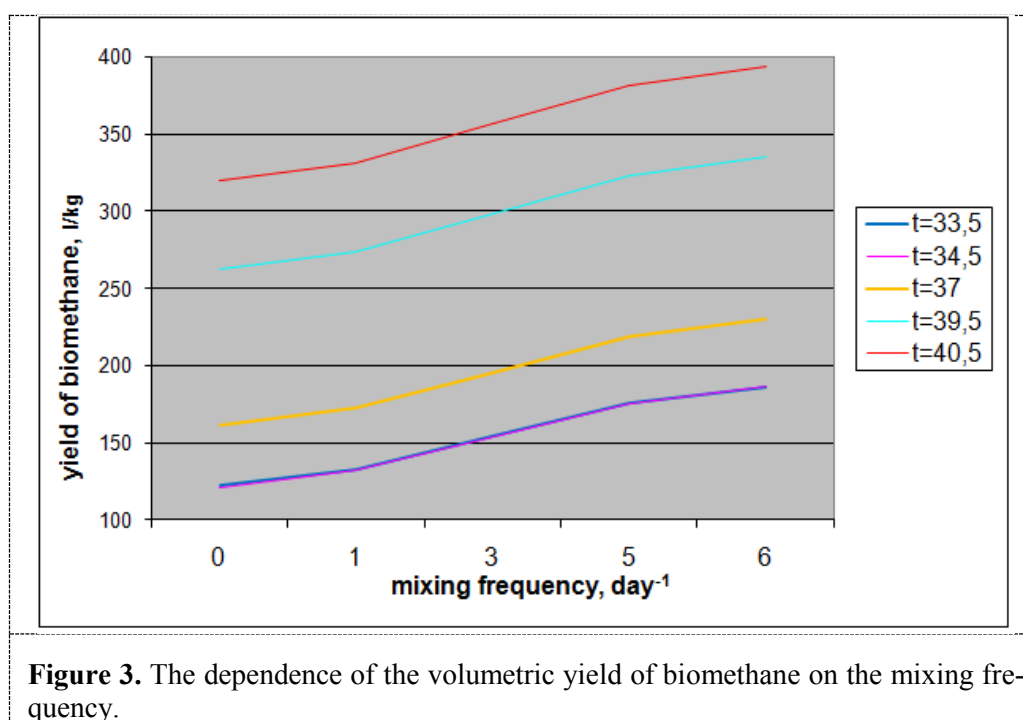
$$V = 5802.62 - 333.03t + 4.88t^2 + 2.13\eta + 0.02\eta^2 + 0.25t\eta. \quad (6)$$

Analysis of the regression equation shows that the greatest influence on the yield of biomethane has temperature, to a lesser extent - the frequency of mixing.

Based on the results of experimental studies, based on the regression equation (6), graphical dependencies are constructed. The graphs make it possible to more fully determine the influence of technological factors on the operation of the anaerobic digester with a bubble-type mixing system.

Figure 3 shows the effect of the mixing frequency of the biomass in the anaerobic digester on the volumetric yield of biomethane at different biomass temperatures.

With an increase in the stirring frequency from 0 to 1 day⁻¹, the yield of biomethane increases by 12.27 l/kg. With an increase in the mixing frequency from 1 to 3 day⁻¹, the yield of biomethane increases by 24.67 l/kg. With an increase in the mixing frequency from 3 to 5 day⁻¹, the yield of biomethane increases by 24.83 l/kg. With an increase in the mixing frequency from 5 to 6 day⁻¹, the yield of biomethane increases by 12.48 l/kg. A change in the mixing frequency from 0 to 6 day⁻¹ entails an increase in the volumetric yield of biomethane by 74.25 l/kg or by 18.9%.



The graph shows that an increase in the mixing frequency promotes a uniform temperature distribution over the volume of the anaerobic digester, which allows to increase the volumetric yield of biogas. However, with more intensive mixing ($\eta > 5$), the volumetric yield of biogas increases slightly.

Figure 4 shows a graph of the dependence of the volumetric yield of biogas on the biomass temperature in the anaerobic digester for various values of the mixing frequency.

With an increase in the biomass temperature from 33.5 to 34.5 °C, the yield of biogas increases by 0.31 l/kg. With an increase in the biomass temperature from 34.5 to 37 °C, the yield of biogas increases by 43.47 l/kg. With an increase in the biomass temperature from 37 to 39.5 °C, the yield of biogas increases by 104.48 l/kg. With an increase in the biomass temperature from 39.5 to 40.5 °C, the yield of biogas still increases by 58.87 l/kg. A change in the biomass temperature from 34.5 to 40.5 °C entails an increase in the volumetric yield of biogas by 207.13 l/kg or by 52.63%.

This relationship is complex. With an increase in temperature from 33.5 °C to 34.5 °C, the volume of biogas produced remains virtually unchanged. Further, there is a significant increase in biogas yield over the entire temperature range from 34.5 to 40.5 °C. A further increase in the yield of biogas is caused by the fact that an increase in temperature leads to an intensive growth of bacteria.

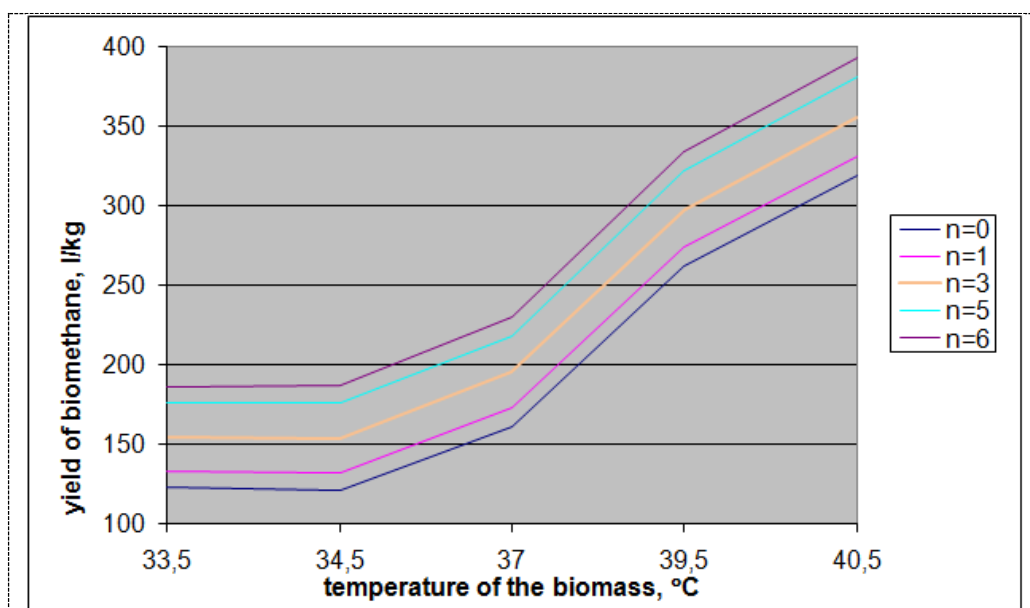


Figure 4. The dependence of the volumetric yield of biogas on the temperature of the biomass.

Analysis of the results of experimental studies shows that the most optimal mode of operation of the anaerobic digester is achieved with $X_1 = + 1.41$; $X_2 = + 1.41$, which provides a high volumetric yield of biogas. This mode can be recommended when using a anaerobic digester for the disposal of agricultural waste.

4. Conclusion

To study the influence of technological factors on the efficiency of a biogas plant, a research program has been developed and an experimental plant has been manufactured. The research program provides for the determination of the effect of temperature and the degree of bubbling of the substrate in the anaerobic digester on the yield of biogas.

As a result of the implementation of the research program, a regression equation was obtained that characterizes the influence of the studied factors on the biomethane yield during anaerobic fermentation in a anaerobic digester equipped with a bubble-type mixing system.

Graphic dependences of the specific yield of biomethane on variable factors were obtained, conclusions were drawn on the effect of each variable factor on the optimization parameter. Rational ranges of values of variable factors for a anaerobic digester with bubbling mixing are established. The most rational mode of operation is achieved with stirring 5-6 days⁻¹, the biomass temperature of 39.5-40.5°C.

Acknowledgments

The study was carried out in the framework of the scholarship of the President of the Russian Federation SP-180.2019.1.

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