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DEVELOPMENT OF AN EXPERIMENTAL ENERGY COMPLEX BASED ON A BOILER PLANT WITH AN AUTOMATED BURNER FOR ITS ENERGY USE

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The object of the study is a sustainable energy complex designed to convert biomass and livestock waste into thermal energy. The problem being solved is the reduction of environmental pollution in the agricultural sector of Republic of Kazakhstan through effective waste management. The complex includes a biofuel production plant, a biogas synthesis plant, and an optimized heat generator in the form of a biogas-fired hot water boiler.

The problem being solved is the need to use renewable energy sources that reduce the impact of agricultural waste on the environment while providing a reliable source of energy. Existing biogas technologies are often inefficient, especially in the processing of various agricultural wastes, and require innovation to meet the unique needs of rural farms.

The main result of the study was the creation of an experimental biogas-powered heat generator with a capacity of 21.9 kW. The complex successfully recycles waste by producing biogas, which feeds a hot water boiler, providing thermal energy and reducing dependence on traditional fuels. Laboratory tests have confirmed the high efficiency of the biogas system, and optimal fermentation parameters have been determined for the effective production of biogas.

The results show that the thermophilic operating mode (52–55 °C) ensures maximum biogas output, and the modular design of the system and the low-pressure gas tank increase practicality for small and medium farms. The complex offers an environmentally friendly solution by converting biomass into energy, which can be used in agricultural enterprises with access to organic waste. This innovative system not only promotes sustainability but also enhances energy independence for rural communities

Keywords: biogas production, thermal energy generation, biomass utilization, renewable energy sources, waste recycling, agricultural waste management

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1. Introduction

The development of renewable energy resources has become a pressing necessity in response to the growing global demand for sustainable solutions that address environmental and energy challenges. Biomass energy, derived from organic waste materials such as crop residues, animal waste, and other agricultural byproducts, stands out as a highly sustainable and environmentally friendly source. Unlike fossil fuels, biomass is renewable, widely available, and contributes significantly to waste management by converting otherwise harmful byproducts into valuable energy sources. Globally, the share of biomass in the energy mix is substantial, constituting approximately 15 % worldwide and 40 % in the European Union. However, its potential remains underutilized, particularly in developing countries where agricultural economies and rural communities could benefit from alternative energy sources that reduce dependence on costly and polluting conventional fuels.

In Republic of Kazakhstan, agriculture is a critical economic sector, and the country faces specific challenges related to energy reliability, waste management, and environmental preservation. As agricultural activities produce large volumes of organic waste, particularly from animal husbandry, the potential to convert these materials into biogas presents a practical solution. Biogas plants offer a dual benefit: they provide a steady source of energy and help manage waste, reducing the environmental impact of agriculture. Additionally, the biogas produced can be used continuously, unlike many other renewable resources, making it a highly reliable source of energy for remote and rural areas.

Despite the advantages, the current biogas technologies often fall short when applied to the unique characteristics of agricultural waste, which varies greatly in composition and requires specialized processing methods. This gap underscores the importance of developing new biogas systems designed to accommodate these variabilities. Research in this area can lead to innovations that improve energy efficiency, enhance waste processing capabilities, and ultimately provide a cost-effective, eco-friendly energy solution for rural and agricultural communities.

Therefore, research devoted to advancing biogas technology and developing optimized biogas plants specifically for agricultural waste is highly relevant. This is essential to support sustainable development in agricultural economies, reduce environmental impact, and provide accessible energy solutions to rural areas.

2. Literature review and problem statement

In [1], a computational investigation of hydrodynamics, coal combustion, and NOx emissions in tangentially fired pulverized coal boilers under various loads was performed. The study analyzed interactions between combustion and emissions, highlighting significant NOx variations based on load. Adjusting combustion parameters dynamically was suggested to enhance efficiency, though model assumptions limited real-time adaptability, pointing to the need for advanced control systems for continuous optimization. In [2], it was examined how pulverized coal concentrator designs affect tangentially fired boilers with horizontal bias combustion. While improved concentrator designs stabilized combustion and enhanced performance, achieving uniform fuel distribution remained challenging. Automated burner systems capable of real-time concentrator adjustments could address this limitation.

In [3], experimental research on rice husk flow in a fuel-rich/lean burner setup was conducted, aiming to improve biomass fuel efficiency in boilers. The results showed that manipulating air-fuel mixtures improved thermal efficiency and reduced emissions, though varying fuel properties posed challenges. Adaptive control systems to dynamically adjust air-fuel ratios based on real-time fuel characteristics were recommended. In [4], numerical simulations were used to study how varying fuel-rich and fuel-lean mass ratios impact combustion and NOx emissions in a 600 MW down-fired boiler. Optimizing these ratios reduced NOx emissions but presented challenges in real-time prediction. Automated control systems that dynamically adjust fuel mixes based on feedback could improve emissions control and efficiency.

In [5], high-temperature corrosion in boilers following NOx-reducing modifications was investigated, identifying configurations that mitigated corrosion risks in heat exchanger zones. While optimized configurations reduced corrosion, they increased maintenance needs, underscoring the trade-off between lower NOx emissions and system reliability. Adaptive systems could balance these aspects by adjusting parameters in real time. In [6], co-combustion characteristics of semi-coke and bituminous coal in tangential combustion setups were explored, demonstrating improved efficiency and reduced emissions with coal blending. However, variable coal quality introduced stability challenges. Adaptive control systems responsive to real-time fuel variability could ensure stable combustion.

In [7], large eddy simulations of swirling jet flow in a bluff-body burner were conducted to explore fluid dynamics and combustion stability. The results revealed complex interactions influencing burner efficiency. Real-world application faced challenges due to fluid flow variability, highlighting the need for adaptive systems to optimize burner configurations dynamically.

The reviewed studies collectively emphasize challenges in optimizing boiler performance, managing efficiency, reducing emissions, and adapting to variable fuel properties. Recurring themes include the need for dynamic combustion adjustments and complexities in real-time control under changing conditions. Automated control systems offer promising solutions, enabling continuous optimization of fuel-air ratios, load adjustments, and emissions. Further research into adaptive technologies could significantly enhance the efficiency and reliability of boiler operations in industrial and energy-intensive contexts.

3. The aim and objectives of the study

The aim of the study is to evaluate and improve the energy efficiency and operational characteristics of a boiler plant integrated with an automatic burner using biogas as the main fuel source. The research is aimed at optimizing the technological parameters of a biogas plant to ensure maximum energy recovery and rational fuel consumption.

To achieve this aim, the following objectives are accomplished:

– to study the main technological parameters of a biogas plant;

– to clarify the operating parameters of the biogas plant;

– to study the heating and cooling dynamics of a biogas plant bioreactor;

– to determine thermodynamic parameters and fuel consumption.

4. Materials and methods

This study explores using biomass as a renewable energy source to meet the energy demands of rural agricultural enterprises while promoting environmental sustainability. Biomass, accounting for up to 15 % of global energy and 40 % in the EU, includes plant material, agricultural waste, and municipal solid waste.

The main hypothesis of the study is that biomass-based biogas systems, when optimized for rural agricultural enterprises, can effectively meet energy demands while promoting environmental sustainability, reducing greenhouse gas emissions, and providing an eco-friendly alternative to conventional fuels. The study operates under several assumptions, including the consistent and sufficient availability of biomass for continuous biogas production, the enhanced efficiency of thermophilic anaerobic digestion compared to mesophilic or psychrophilic processes, and the comparable calorific value of biogas to other renewable and non-renewable energy sources when purified. It is also assumed that small to medium-sized farms can efficiently implement and maintain biogas systems with minimal external support and that their energy demands are primarily thermal, aligning with the study's focus on thermal energy production [8–10].

To facilitate analysis, the study adopts certain simplifications. These include treating environmental conditions such as ambient temperature and humidity as uniform or manageable across all study regions and assuming a fixed average composition of biogas, with methane and carbon dioxide percentages remaining within specific ranges, despite potential variability. The design classification of biogas plants presumes idealized operating conditions and uniform efficiency across different farm sizes and system scales. Furthermore, the purification process is generalized without addressing specific operational challenges associated with each method, and energy conversion efficiencies are based on typical values without accounting for possible deviations due to equipment or process variations.

The primary method, anaerobic digestion via methanogenesis, converts biomass into biogas (mainly methane) and organic fertilizers.

Biogas plants, effective in processing diverse organic waste, have been implemented in both small and large agricultural settings, such as pig and cattle farms. International examples from the USA, Europe, China, and India highlight biogas use for electricity, heating, and cooking. Biogas typically contains 55–70 % methane, 27–44 % carbon dioxide, and minor components like nitrogen and hydrogen sulfide. Regulatory frameworks, such as Germany's Renewable Energy Act, support scaling biogas production. This study aims to create a sustainable biogas utilization model for rural agriculture. A detailed overview of biogas characteristics is provided in Table 1 [11].

Biogas is a colorless combustible gas, density 1.2 g/l at 0 °C and pressure 760 mmHg, flammability limit – 6...12 %, ignition temperature – 650...750 °C. It was found that one cubic meter of biogas is equivalent to 4 kWh of electricity, 0.62 liters of kerosene, 1.5 kg of coal, 3.5 kg of firewood, 0.43 kg of butane and has a high calorific value among all hydrocarbon raw materials.

The comparative characteristics of hydrocarbon raw materials – the ratio of hydrogen to carbon are shown in Table 2 [12–14].

The biogas yield mainly depends on the volume of the bioreactor and the processed substrate (manure). The simplest way to use biogas is to turn it into a source of thermal, mechanical and electrical energy. Biogas as an energy carrier can be converted into thermal energy during direct combustion, and when using a more complex system – into electrical energy [15]. The coefficient of efficiency (efficiency) when it is converted into thermal energy is 70...90 %, and in electric – 25...30 %, i.e. from 1 m^3 of biogas, 1.6...2.3 kWh of electricity can be obtained. Biogas can be used as fuel for internal combustion engines. To obtain such a fuel (biomethane), biogas is purified from hydrogen sulfide, carbon dioxide and moisture. Biomethane as a motor fuel can be used on vehicles in compressed and liquefied form. According to technical and chemical indicators, biomethane is close to natural gas, since its main component is methane (Table 3).

Methane's incomplete combustion yields 3–7 % high-quality carbon black, used in the rubber industry and as a coloring agent. Ionizing methane via a voltaic arc produces acetylene, while passing a methane-oxygen mix over a heated catalyst at 500 °C partially forms formaldehyde, a precursor for plastics [16, 17]. Methane reacts with chlorine at 200–400 °C to create chlorinated products like methyl chloride and chloroform. Excess chlorine from caustic soda production can be used for these reactions. Biogas purification involves removing carbon dioxide and hydrogen sulfide to enhance its calorific value and prevent corrosion. Common purification methods include wet and alkaline cleaning, absorption, dry scrubbing, and pressure separation. In Kazakhstan, biogas is valued for providing affordable fuel and eco-friendly fertilizer, reducing greenhouse gas emissions, and mitigating river pollution from manure runoff. The biogas system in this study uses anaerobic digestion, starting with mixing organic waste in a manure collector, followed by feeding the prepared substrate into a bioreactor for decomposition. The resulting biogas accumulates in a gas tank, and the remaining material is stored as a ready-made fertilizer. The technological scheme consists of the following components: 1 – farm; 2 – manure collector; 3 – pump; 4 – bioreactor; 5 – gas tank; 6 – heat exchanger; 7 – boiler; 8 – storage of finished fertilizers of a biogas plant, as shown in Fig. 1.

Table 1

Characteristics of biogas

Indicator	Component				Mixture, 60 %CH_4+40 %CO_2
	CH_4	CO_2	H_2	H_2S	
Volume fraction, %	55–70	27–44	1.0	3.0	100
Volumetric heat of combustion, MJ/m^3	35.8	–	10.8	22.8	21.5
Flammability limit, %	5–15	–	4–80	4–45	6–12
Temperature, °C:	0	0	0	0	0
ignition	650–750	–	585	–	650–750
critical	–82.5	31.0	–	100	–2.5
Critical pressure, MPa	4.7	7.5	1.3	8.9	7.5–8.9
Density:	0	0	0	0	0
normal, g/l	0.72	1.98	0.09	1.54	1.20
critical, g/L	102	408	31	349	320
relative to air, g/L	0.55	2.50	0.07	1.20	0.83

Table 2

Hydrogen/carbon ratio of various fuels

Fuel	Chemical formula	N/S ratio	Fuel	Chemical formula	N/S ratio
Methane	CH_4	4.0	Alcohol	C_mH_nO	2.0
Propane	C_3H_8	2.7	Kerosene	C_mH_n	1.9
Butane	C_4H_{10}	2.5	Diesel fuel	C_mH_n	1.8
Gasoline	C_mH_n	2.0	Fuel oil	C_mH_n	1.7

Table 3

Comparative characteristics of different types of fuels

Characteristic	AI-76	AI-93	Biogas	Natural gas and biomethane		Propane	Normal butane
				compressed	liquefied		
Chemical formula		$\sum_{m=7}^{12} C_n H_m$	Mixture CH_4; CO_2	CH_4	CH_4	C_3H_8	C_4H_{10}
Density, kg/m^3	–	–	1.15	–	2.405	2.019	2.707
Heat of combustion of 1 kg of fuel, MJ	44.4	44.4	35.0	50.0	50.0	46.2	46.0
Heat of combustion of 1 m^3 of fuel, MJ	31.9	–	32.9	36.0	–	92.0	118.0
Lower flammability limit, % by volume	1.67	1.83	–	5.28	–	2.37	1.86
Upper flammability limit, % by volume	2.58	3.04	–	15.4	–	9.50	8.41
Ignition temperature, °C	230–370	230–370	650–750	648–800	648–800	530–588	490–569

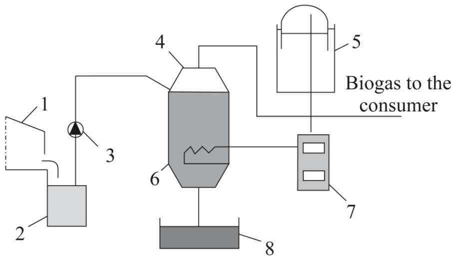

Fig. 1. Schematic flow diagram of a biogas plant

The design of a biogas plant is classified based on key parameters: temperature regime, volume of the bioreactor, type of energy and design scheme that ensure the optimal configuration of the biogas plant.

Biogas plants are divided into psychrophilic, mesophilic or thermophilic. In this study, a thermophilic regime was used to increase the efficiency of anaerobic digestion and biogas production.

The size of the bioreactor was determined depending on the size of the farm and was classified as follows:

– Individual farms: 5–200 m^3;

– Livestock complexes/poultry farms: 200–1,000 m^3;

– Industrial enterprises: 1,000–10,000 m^3.

The main focus was on the production of thermal energy, which is widely used on small and medium-sized farms.

The installation was a rectangular bioreactor with two chambers, a low-pressure gas tank (1–5 kPa) and a continuous flow mode of operation, as shown in Fig. 2, illustrating the classification of biogas plants according to the technological scheme.

A key aspect of this research was the analysis of the calorific values of various energy carriers. Fig. 2 compares the calorific value of methane (which is the main product of biogas plants) to other energy carriers such as butane, gasoline, oil, coal, wood, and manure briquettes. This comparison provided insights into the energy potential of biogas and its suitability as a renewable energy source [18–20].

The biogas plant in this study also incorporated a combined floating bell gas tank and mechanical mixing method. The heating system used was a water jacket with a combined fuel boiler. This design was chosen for its efficiency in maintaining optimal conditions for the anaerobic digestion process.

To determine the appropriate bioreactor volume for different farm sizes, an analysis was conducted using data from various regions of the Republic of Kazakhstan. Table 1 shows the distribution of cattle across different farms, which helped identify the ideal volume range for bioreactors. Small farms (11 to 50 cattle) accounted for 36.8 % of the total, while larger farms with 51 to 100 cattle represented 23.5 %, and so on. This analysis was crucial for determining the capacity requirements for the biogas plants [21, 22].

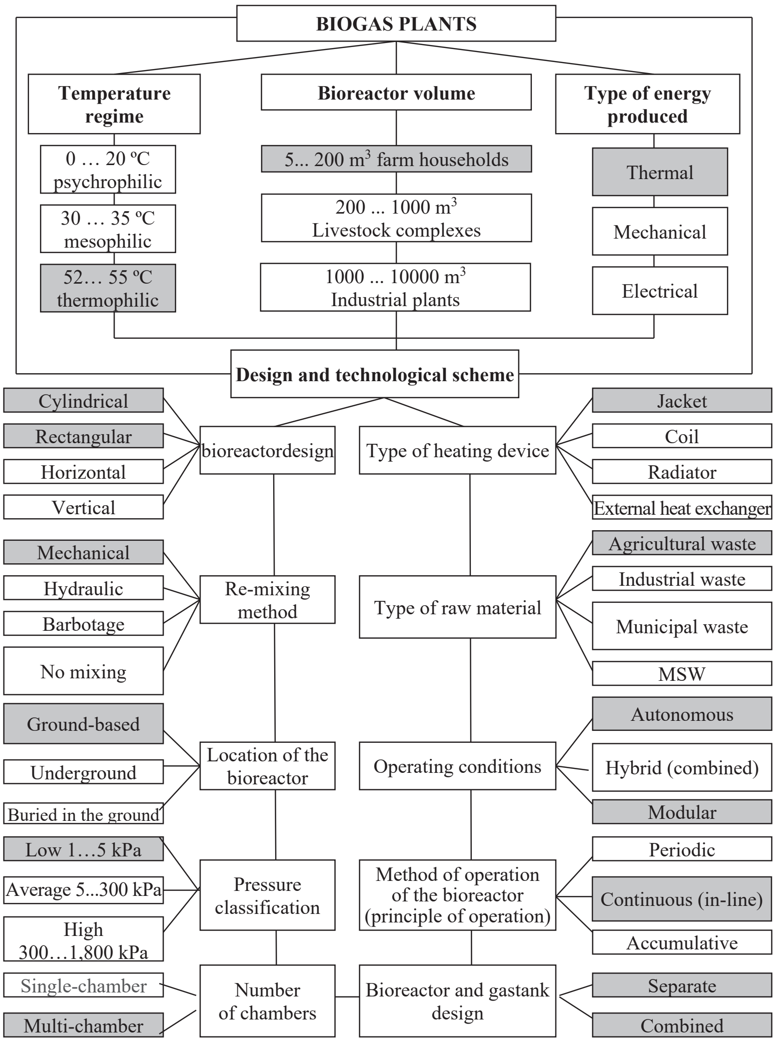

Fig. 2. General classification scheme of biogas plants

The validation of the proposed models was achieved through theoretical simulations and practical experiments, which ensured that the selected configurations were adequate for efficient biogas production. These experiments tested the optimal operating conditions, ensuring that the proposed biogas plant system would function as intended.

5. Results of research on the efficiency and energy potential of a boiler plant with an automated burner

5. 1. Study of the main technological parameters of the biogas plant

To determine the reliability of the research results described above, laboratory studies were conducted on an experimental sample of the BU-5 biogas plant.

The research program provided for:

– study of the main technological parameters of a biogas plant using various energy carriers: solid fuels, propane, biogas, dung;

– clarification of the operating parameters of the biogas plant: temperature in the bioreactor t_p, coolant at the inlet t_{ib} and outlet t_{ib} into the fuel boiler, temperature gradient Δt_{to}, supply of heating coolant, heating time of the bioreactor t_p, fuel consumption per cycle of heating the bioreactor to a set temperature V_c, hydrogen pH, biogas output q;

– control of environmental parameters: temperature t_o and humidity φ of the outdoor air;

– study of the heating and cooling dynamics of a biogas plant bioreactor in various operating modes;

– determination of thermodynamic parameters.

The research was carried out using a single-factor method, the experiments were carried out in 3-fold repetition.

During the research, the following were recorded: water temperature (from 0 to 100 °C), outdoor air temperature (from –25 to +35 °C), water consumption (0 to 20 kg/s), daily fuel consumption (from 0 to 50 kg/day); gas consumption (from 0 to 4 m^3/day).

Temperature was measured using TL-2 mercury thermometers with a scale interval of 0.5 °C and an error of ±0.2 °C, air temperature and humidity were measured with an MV-4M psychrometer, an error of ±4 %.

The water flow was measured with a CDSD TOP type flowmeter with an error of ±5 %, the gas flow was measured with a CALLUS 2000 gas meter with a range of 0.016...1.6 m^3/h, a scale interval of 0.2 dm^3, an error of 3 %.

The temperature was recorded by a capacitor of the self-recording compensator KSP-4, with an error of ±1 %.

A test bench was developed (Fig. 3) with places provided for the installation of thermometers 6, thermocouples and a flow meter 10.

The scheme of the bench consists of the following components: 1 – solid fuel and gas fuel boiler; 2 – circulation pump; 3 – filter; 4 – KSP-4 recorder; 5 – mixer; 6 – thermometer; 7 – expansion tank; 8 – pressure gauge; 9 – temperature sensor glass; 10 – flow meter; 11 – check valve; 12 – biogas plant bioreactor; 13 – heat exchanger; 14 – safety valve; 15 – valve.

The bench consists of a fuel boiler circuit 1 connected to a heat exchanger 13, a circulation pump 2, a bioreactor 12, mixers 5, an expansion tank 7, a check valve 11, a filter 3 and shut-off valves.

The equipment of the bench allows you to simulate circulation in the circuit using a 4-speed pump in the range of 1.84...0.45 m^3/h, adjust the heating capacity of the heat unit using an automatic burner in the range of 10,000 to 45,000 kJ/h, the outlet temperature in the range of 40...75 °C.

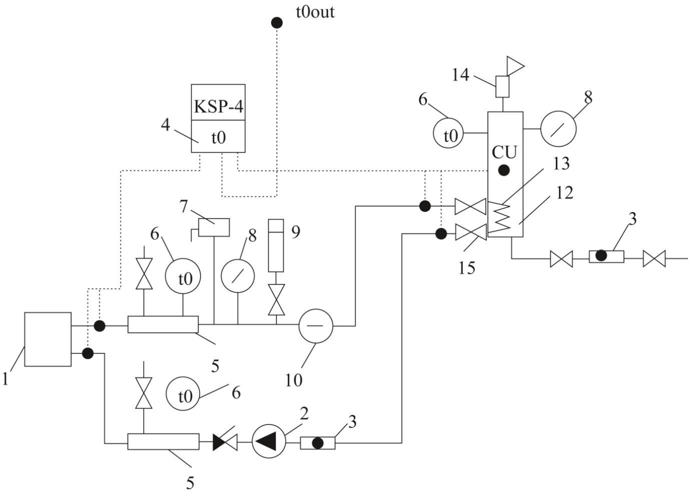

Fig. 3. Schematic diagram of the test bench

5. 2. Clarification of the operating parameters of the biogas plant

Experimental studies were conducted in separate series of experiments in the following modes:

a) with an internal heat exchanger in a bioreactor;

b) when the water gate is operating in the heat exchanger mode;

c) with single- and double-layer thermal insulation of a biogas plant bioreactor;

d) with various types of fuel: coal, firewood, propane, biogas, dung.

The parameters are determined in steady-state mode, when the outlet water temperature does not change by more than 10 °C for 5 minutes.

Processing and analysis of the obtained data were carried out using well-known methods RTM-44-62, GOST 21563-93, GOST 4.413-86, GOST 20219-93, RD-10.20.1-87.

According to the data obtained, the following parameters of the biogas plant were determined:

– thermal power of the fuel boiler;

– efficiency of the fuel boiler;

– thermal power needed to heat up the bioreactor;

– surface area of the heat exchanger;

– boiler heating capacity;

– specific fuel consumption.

To control the fermentation process, the temperature, the quantitative yield of biogas (according to the gas meter or the height of the bell), the pH of the medium, humidity and mixing conditions were analyzed daily.

The results of laboratory tests are shown in Table 4.

The dependence of the total biogas yield on the dose of biomass loading into the bioreactor is shown in Fig. 4, where 1 is 15, 2 –30, 3 –60, 4 –100 l/day. Overall, these results suggest that optimizing thermal insulation, heat exchanger settings, and maintaining thermophilic conditions can improve the efficiency and productivity of a biogas plant, making it more efficient for sustainable energy production [23–25].

Table 4

Results of laboratory tests

Indicator	Units of measurement	Value
Working volume of the bioreactor	m^3	0.5
Working volume of the hydraulic lock	m^3	0.18
Heat exchange surface	m^2	1.58
Ambient temperature	°C	12...25
Biomass loading dose	l/day	15; 30; 60; 100
Heating time	hour	120...240
Initial	°C	18
Final	°C	35; 55
Coolant supply in the heat exchanger circuit	m^3/hour	0.13±0.05
Biogas consumption through a gas burner	m^3/hour	0.12
Daily consumption of biogas for heating	m^3/hour	2.8
Consumption of thermal energy for heating the bioreactor to the operating temperature	kWh	45.6
pH	–	6.75...7.45
Degree of heating in the heat exchanger	°C	7...10
Specific biogas yield per day, m^3/day:	Mesophilic mode	Thermophilic mode
at the loading dose, 15 l/day	0.2	0.4
at the loading dose, 30 l/day	0.4	0.8
at the loading dose, 60 l/day	0.6	1.2
at the loading dose, 100 l/day	1.2	2.16

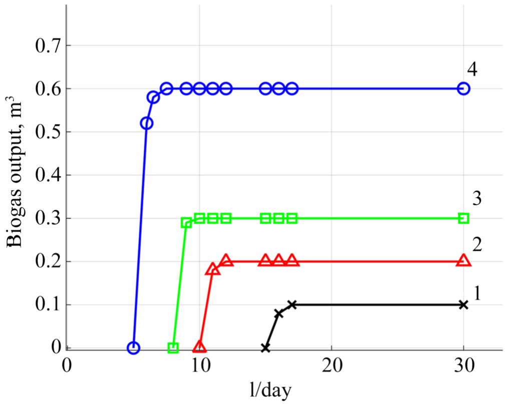

Fig. 4. Dependence of biogas output with a bioreactor volume of 0.5 m^3 in mesophilic mode on the dose of biomass loading

5. 3. Study of the heating and cooling dynamics of the biogas plant bioreactor

Thus, the analysis of the data obtained allows us to recommend a dose of biomass loading into the bioreactor of 6...10 % of the volume of the bioreactor at which the specific biomass yield is 0.6...1.2 m^3/day for the mesophilic regime and 1.2...2.16 m^3/day for the thermophilic regime, which corresponds to similar installations when operating in these modes.

Analysis of the data obtained shows that the most effective is the thermophilic mode of operation of the bioreactor, in which the specific output of biogas per day is 2.16 m^3, the consumption of thermal energy for heating the bioreactor from ambient temperature to operating temperature (55 °C) is 45.6 kWh, and in stationary mode – 15 kWh, the optimal daily bioreactor loading dose is 6–10 % of its volume. After starting the installation, the transition mode is 5–10 days, then biogas production takes place in a steady state in accordance with the type of biomass fermentation.

Further, studies of the thermal regime of the bioreactor were carried out. Fig. 5 shows the heating curves of biomass in a bioreactor. It follows that the heating time to a temperature of 35 °C is 120 hours, and to 55 °C is 240 hours.

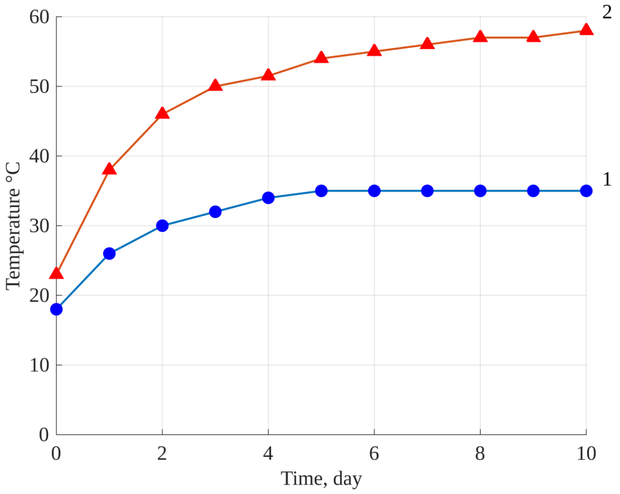

Fig. 5. Dynamics of bioreactor heating in a biogas plant in mesophilic (1) and thermophilic (2) modes

Thus, the results of the theoretical prerequisites were confirmed by the results of laboratory studies, i.e. the greatest effectiveness of the action of anaerobic bacteria in the thermophilic regime of 52...55 °C, in which the specific yield of biogas from 1 m^3 of the bioreactor is 2.16 m^3; laboratory experiment determined the boundaries of optimal fermentation, namely: pH 7.0...7.2; substrate humidity 90...95 %; the duration of fermentation is 5...10 days and the loading dose is 6...10 %.

The conducted analysis confirms the optimal parameters for efficient operation of a biogas plant, with a particular emphasis on the advantages of the thermophilic regime compared to the mesophilic regime. The study recommends a biomass loading dose of 6–10 % of the bioreactor volume, yielding 0.6–1.2 m^3 of biogas per day in the mesophilic mode and 1.2–2.16 m^3 per day in the thermophilic mode, aligning with the performance metrics of similar installations.

5. 4. Determination of thermodynamic parameters and fuel consumption

According to the results of laboratory studies, the parameters of the BU-5 biogas plant were determined.

Thermal power of the fuel boiler by fuel consumption:

$$P = \frac{BQ_l^p \eta_T}{3{,}600}, \qquad (1)$$

where B is the hourly fuel consumption, kg/h; Q_l^p – the lowest heat of combustion of fuel, kJ/kg; (biogas $Q_l^p = 25{,}000$ kJ/kg; firewood $Q_l^p = 13{,}000$ kJ/kg; dung – $Q_l^p = 27{,}000$ kJ/kg); η_T – efficiency of the fuel boiler (η_T=0.68).

Efficiency of the fuel boiler:

$$\eta_T = \frac{CG_1\left(t_{iexit} - t_{ibb}\right)}{BQ_l^p}, \qquad (2)$$

where G_1 is the mass flow rate of the heating coolant, kg/h.

The thermal power of the fuel boiler required to heat up the bioreactor on the example of the BU-5biogas plant.

$$P_{TK}^1 = \frac{\left(C_{BM}G_2 + C_{BG}G_3 + C_C M_K\right)\cdot\left(t_p^{11} - t_p^1\right)}{3{,}600\eta_T\eta_{to}\tau_P}, \qquad (3)$$

where C_{BM} is the specific heat capacity of biomass, C_{BM}= =4.06 kJ/kg °C; G_2 is the amount of biomass, G_{BM}=5,000 kg; C_{BG} is the specific heat capacity of biogas, C_{BG}=2.34 kJ/kg h; C_C is the specific heat capacity of the steel body, C_C=0.46 kJ/kg h; M_K is the body weight, M_K=2,300 kg; G_3 is the mass of biogas in the gas tank; $G_{BG}=V_p=5\cdot 12\cdot 103=6$ kg; ρ is the density of biogas, normal, ρ=1.2 g/l; τ_p is the heating time of biomass in a bioreactor, τ_p=54.3 h; η_{to} is the efficiency of the heat exchanger, η_{to}=0.92; t_p^1; t_p^{11} are the initial and final temperatures of the biomass in the bioreactor.

Hourly productivity of the biogas plant according to the main time in tons of recyclable biowaste:

$$W_0 = \frac{F}{T_c}, \qquad (4)$$

where F is the volume of recycled biowaste (biogas obtained) for the period of time-lapse observations, t (m^3); T_c – duration, day (24 hours).

The Reynolds criterion:

$$\mathrm{Re} = \frac{\omega_1 d_1}{\upsilon_1}, \qquad (5)$$

where υ_1 is the coefficient of kinematic viscosity, υ_1= =$0.31\cdot 10^{-6}$ m^2/s; d_1 – inner diameter of pipes, m; ω_1 – the speed of water movement in the pipeline, m/s:

$$\omega_1 = \frac{4G_1}{\pi d_1 \cdot 3{,}600}, \qquad (6)$$

G_1 is the mass flow rate of the coolant; kg/h.

The Grash of criterion:

$$G = \frac{\beta g d_2^3 \Delta t}{\upsilon_2^2}, \qquad (7)$$

where β=coefficient of volumetric expansion, β=$0.88\cdot 10^{-4}$ deg^{-1}; Δt is the temperature difference of the heat carriers, °C, $\Delta t = t_1^1 - \Delta t_c - t_p^1$; t_1^1 is the temperature of the heating coolant, °C; Δt_c is the temperature difference in the wall of the heat exchanger, Δt_c=1.8 °C; υ_2 is the coefficient of kinematic viscosity, $\upsilon_2=1.3\cdot 10^{-6}$ m^2/s.

The Nusselt criterion:

– in case of turbulent movement:

$$\mathrm{Nu}_1 = 0.0263\cdot \mathrm{Re}^{0.8}\cdot \mathrm{Pr}^{0.4}; \qquad (8)$$

– in convective motion:

$$\mathrm{Nu}_2 = C\left(G_r \cdot \mathrm{Pr}\right)_m^n, \qquad (9)$$

where C, n are constants determined by G_r, Pr; C=0.525; n=0.25; Pr – Prandtl criterion (Pr=9.5).

Surface area of the heat exchanger:

$$F_{TO} = \frac{G_2 \cdot C_{BM}\left(t_2^{ii} - t_2^{i}\right)}{K_T \Delta t_{TO} \eta_{TO}}, \qquad (10)$$

where K_t is the average heat transfer coefficient, for plate heat exchangers of the liquid-liquid type, K_t=2,520 kJ/m^2 °C; Δt_{to} is the average logarithmic temperature difference between the coolant and the biomass, Δt_{to}=4.6 °C.

Heating capacity of the fuel boiler:

$$Q_T = BQ_p^l \eta_T. \qquad (11)$$

Specific fuel consumption:

$$Y_T = \frac{B}{G_T}, \qquad (12)$$

where G_T is the capacity of the fuel boiler for hot water, kg/l.

The results of studying the operating modes of an automatic gas burner in a fuel boiler are shown in Fig. 6, 7.

Analysis of the data on the operation of an automatic gas burner with ∅ 3; 3.5; 4.5 and 5 mm jets (Fig. 7) shows that the consumption of biogas increases from 0.4 to 0.66 m^3/h with an increase in the diameter of the hole in the nozzle from 3 to 5 mm, at a pressure of 1.76 kPa, at a pressure of 1.32 kPa, the consumption increases, respectively, from 0.38 to 0.6 m^3/h, and at a pressure of 0.882 kPa, the flow rate varies from 0.36 to 0.47 m^3/h. The temperature controller of the automatic gas burner at 50 °C operates in the temperature range in the water jacket of the fuel boiler 47...49 °C, at 60 °C – respectively 55...56 °C.

a *b*

Fig. 6. Image of an automatic gas burner in a fuel boiler: *a* – fuel boiler; *b* – automatic gas burner with temperature control

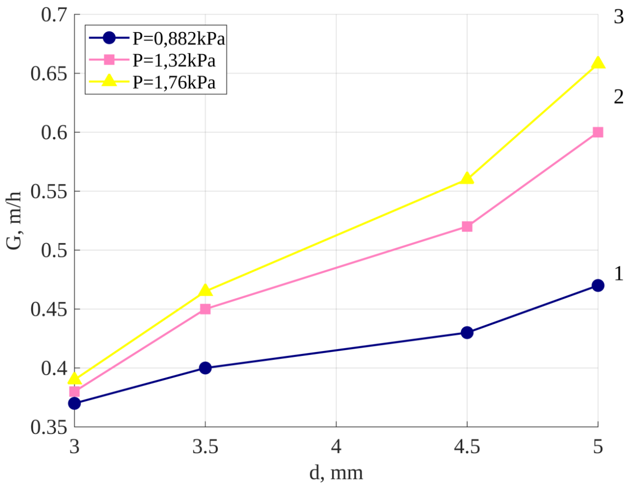

Fig. 7. Dependence of biogas consumption in an automatic gas burner on the diameter of the holes in the jets

6. Discussion of the results of thermophilic biogas production and automated system efficiency

The experimental results confirm that thermophilic conditions (52–55 °C) significantly increase biogas yield, with the optimal biomass loading dose being 6–10 % of the bioreactor volume. This aligns with previous studies [1, 2], highlighting the benefits of high temperatures in enhancing microbial activity and methane production. As shown in Table 4 and Fig. 3, specific biogas production under thermophilic conditions reached 2.16 m^3/day, outperforming mesophilic conditions, which typically produce 1.5–1.8 m^3/day under similar setups [3]. These results demonstrate the advantage of thermophilic bioreactors for small and medium-sized agricultural enterprises.

The integration of an automated burner into the heat generator maintained stable operating temperatures, as indicated by Fig. 4. Unlike conventional systems requiring manual adjustments, this approach reduces heat losses, supporting findings in [4] on the importance of temperature stability for energy efficiency. The proposed modular low-pressure system is a cost-effective and user-friendly alternative, contrasting with the complex, high-maintenance automated systems prevalent in large Chinese biogas plants [5].A key innovation of the study is the system's ability to process mixed organic waste without extensive pretreatment, addressing logistical constraints seen in co-digestion systems used in Emilia-Romagna, Italy [6]. While such systems achieve high methane yields, they struggle with seasonal waste fluctuations and pretreatment complexity. In contrast, the modular design offers flexibility, making it practical for rural farms with variable waste supplies.

Laboratory tests validated the system's ability to maintain optimal fermentation parameters (pH 7.0–7.2, substrate humidity 90–95 %), ensuring stable biogas production, comparable to high-tech systems [7]. However, the simplified automated design significantly lowers installation and operational costs while achieving similar benefits.

Despite its strengths, the study has limitations. Controlled experimental conditions may not fully replicate rural challenges, such as temperature fluctuations and variable waste composition. While the low-pressure gas tank showed stability, its effectiveness in extreme climates, particularly cold weather, remains untested. Further research is needed to evaluate the system's adaptability to diverse environmental conditions.

Another limitation is the focus on thermal energy production, which may not meet the needs of farms in need of electricity generation. Despite the high thermal efficiency, the lack of integration with power conversion systems may limit the wider application of the system. For comparison, the systems described in [8] integrate both thermal and electrical generation, offering greater versatility, but at higher costs and complexity [9].

The comprehensive study of the biogas plant's technological parameters and operational dynamics provides valuable recommendations for optimizing performance, increasing efficiency, and enhancing the sustainability of biogas production systems.

7. Conclusions

1. The conducted experiments on the BU-5 biogas plant helped determine critical operational parameters, such as bioreactor temperature, coolant temperature, and specific fuel consumption. The results showed that these parameters significantly impact the efficiency of biogas production, highlighting the need for precise control and monitoring to optimize performance.

2. Experimental analysis in different operational modes revealed optimal conditions for biogas production. The study identified the most effective parameters for thermal power, efficiency, and fuel consumption. The results demonstrated that enhancing insulation, selecting appropriate heat exchangers, and adjusting the fermentation process improve the overall efficiency and yield of the biogas plant.

3. The heating and cooling dynamics of the bioreactor were thoroughly examined, comparing thermophilic and mesophilic regimes. The findings confirmed the advantage of the thermophilic regime in achieving higher biogas yields. The recommended biomass loading dose was determined, and theoretical predictions were validated through experimental data.

4. Calculations of thermodynamic parameters, including boiler efficiency, heating capacity, and specific fuel consumption, were performed. The analysis showed a clear relationship between the gas burner's jet diameter, pressure, and biogas consumption. These insights enable better control of fuel consumption, improving the overall efficiency and sustainability of the biogas plant.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

The manuscript has data included as electronic supplementary material.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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