

Heat Recovery of Low-Grade Energy Sources in the System of Preparation of Biogas Plant Substrates

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ABSTRACT

Preliminary preparation of waste for anaerobic digestion at thermophilic temperature conditions is the most energy-intensive stage of the process of anaerobic bioconversion of production and consumption waste organic matter; therefore, the search for ways to reduce energy consumption at this stage remains an urgent task. The article proposes a technological solution to maintain the temperature regime of the digester operation due to the utilization of existing waste low-grade energy sources using a compression heat pump. The flow diagram of the experimental biogas plant is shown, and a description of its operation is given. The dependences of the absolute and specific rates of heating of the influent and cooling of the effluent on the initial temperature of the effluent are given. The principal possibility of maintaining the temperature regime in the digester is shown by using the heat recovery of the effluent using a compression heat pump.

KEYWORDS

Anaerobic Processing, Biogas, Effluent Heat, Energy Efficiency, Heat Pump, Heat Recovery, Organic Waste, Preliminary Preparation of Waste

INTRODUCTION

In recent years, the attention of society has been increasingly drawn to solving two inextricably linked problems – the prevention of depletion of natural resources and the protection of the environment from anthropogenic pollution. The rapid use of reserves of natural fuel, the restriction of construction of hydro and nuclear power plants have aroused interest in the use of renewable energy sources, including the huge masses of organic waste generated in agriculture, industry, and municipal utilities. (Nozhevnikova et. al., 2016) The negative impact of agricultural activities on the environment is associated not only with the increasing consumption of natural resources, but also, to a greater extent, with the formation of liquid and solid waste from agricultural and processing industries. In particular, raising animals, processing meat and dairy products, producing beer, sugar, starch, etc. are accompanied by the formation of a large amount of wastewater. (Izmaylov et. al., 2018; Artamonov et. al., 2018) In this regard, the use of methods for the biological conversion of organic waste with

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the production of biogas and high-quality organic fertilizers while simultaneously solving a number of environmental issues from pollution is very promising (Nozhevnikova et. al., 2016).

According to the Strategy for Sustainable Development of Rural Areas of the Russian Federation for the period up to 2030, in the field of development of engineering infrastructure, it is necessary to maximize the use of non-traditional energy sources for power supply of rural settlements, including biogas plants.

The annual volume of agricultural waste is about 152 million tons. Livestock farms are the main source of organic waste (manure, droppings): cattle farms - 91 million tons; poultry farms - 32 million tons; pig farms - 26 million tons.

In the register of qualified generating renewable energy sources there is only one biogas power plant “Luchki” in the Belgorod region with a capacity of 2.4 MW with an annual consumption of 93 thousand tons of waste. At the same time, the total annual consumption of animal waste for biogas production is only 0.17% from the volume of organic waste generated at Russian agricultural enterprises

Thus, at present, the actual use of organic waste, potentially suitable for biogas production, is 2-3 orders of magnitude lower than the existing potential for organic waste. (Namsaraev et al., 2018a; Namsaraev et al., 2018b)

A recent trend in sustainable bioenergy solutions is the renewed interest in using anaerobic digestion (AD) technology to treat agricultural wastes and biomass for biogas production (Edwards et al., 2015; Smith et al., 2015)

Unlike other renewable technologies, AD can uniquely capture harmful methane (CH₄) and nitrous oxide (N₂O) emissions released from manure, while simultaneously producing renewable bioenergy (Chadwick et al., 2011; Gerber et al., 2013; Moral et al., 2012).

Table 1 highlights the priority methods for intensifying the process of anaerobic processing of agro-industrial complex wastes, which make it possible to provide an increased yield of biogas with a simultaneous reduction in the consumption of external energy sources due to the recovery of existing waste sources of low-potential energy. (Badmaev, 2018; Kovalev et al., 2020d)

Table 1. Methods for intensifying the process of anaerobic bioconversion

The main directions of intensification of the process of anaerobic processing of agricultural waste	Priority methods of intensifying the process of anaerobic processing of agricultural waste
<ul style="list-style-type: none"> - study of the process of fermentation of organic waste with a concentration of solid particles of 30-50%; - multistage anaerobic digestion of organic waste based on the vital activity of acidogenic and methane-forming bacteria; - creation of highly active strains of microorganisms grown in special cultivators and introduced in the form of a starter culture into the digester; - study of the process of methane fermentation with the participation of psychrophilic bacteria. 	<ul style="list-style-type: none"> - the use of various technological solutions, including the use of heat pumps, to reduce the consumption of thermal energy for the own needs of anaerobic bioconversion systems; - the use of the electromagnetic field of the vortex layer apparatus during the preprocessing of organic waste to maximize the transfer of organic substances into a dissolved state; - introduction of conductive materials into the substrate during pretreatment in vortex layer apparatus in the form of ferromagnetic microparticles, which are a catalyst for the process of anaerobic bioconversion; - the use of direct interspecies electron transfer in anaerobic bioreactors due to the influence of direct current; - recycling of the digested sludge and the use of anaerobic biofilters in the digestion chamber of the digester.

The stabilization of sewage sludge in anaerobic digestion tanks at different temperature ranges, enrichment of the methane content and purification of the produced biogas, and optimization of the total biogas production through the use of anaerobic digestion systems were discussed in several published studies (Sung et al., 2017; Latha et al., 2019; Alqaralleh et al., 2018; Elalami et al., 2020;

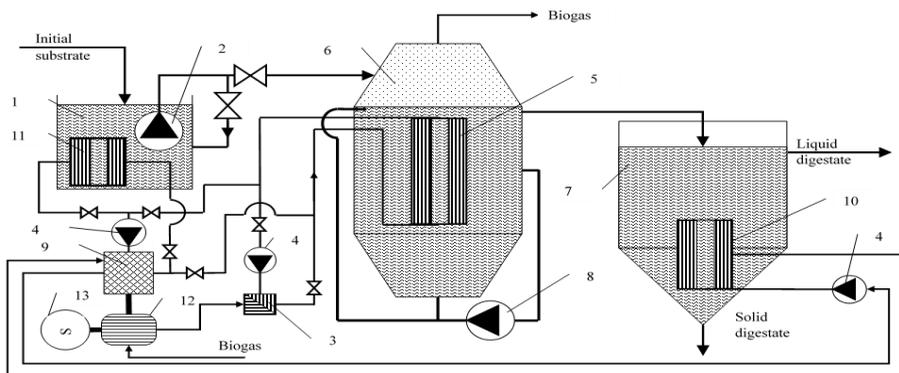
Liu et al., 2018). The main energy costs in a biogas plant are used to heat the daily loading dose, and only up to 40% of the biogas produced can be used for other purposes (Kovalev, 2014; Chen et al., 2014; Carrillo-Reyes et al., 2019)

Heat pumps are included in the “List of facilities and technologies that relate to facilities and technologies of high energy efficiency” (approved by the Government of the Russian Federation of June 17, 2015 No. 600).

Therefore, the maintenance of the temperature regimes of the elements of the anaerobic bioconversion system can be carried out through the use of the developed improved heat supply system of the biogas plant. (Holik et al., 2021; Siddiqui et al., 2020; Ishikawa et al., 2021; Kovalev et al., 2020b; Kovalev et al., 2021; Weinand et al., 2019)

The technological scheme of the developed improved heat supply system for a biogas plant for processing bedding cattle manure with heat recovery of the effluent using a compression heat pump is shown in Figure 1.

Figure 1. Technological diagram of the biogas plant heat supply system



1 - preheating tank; 2 - loading pump; 3 - block of heat recovery from the internal combustion engine; 4 - coolant circulation pump; 5 - bioreactor heat exchanger; 6 - anaerobic bioreactor; 7 - effluent settler; 8 - pump for mixing the substrate; 9 - compression heat pump; 10 - heat exchanger-cooler; 11 - heat exchanger-heater; 12 - internal combustion engine; 13 - electric generator.

A biogas plant includes, among other things:

- preheating tank in which the heat exchanger is mounted;
- an anaerobic bioreactor with an internal heat exchanger for maintaining the temperature regime of fermentation and an unloading device that is connected to the effluent settler.

The heat from the heat recovery unit from the internal combustion engine in the winter period (from December to February inclusive) is used to compensate for heat losses through the enclosing surfaces of the bioreactor (the compression heat pump works only for preliminary heating of the substrate), and in the summer period - for the needs of consumers.

A heat exchanger is mounted in the effluent settler to extract heat energy from the effluent. The heat exchanger is connected via pipelines to the heat pump evaporator. In the heat pump evaporator heat exchange takes place between the treated water and the low-grade refrigerant, which, after increasing the energy potential in the compressor of the heat pump, is sent to the heat pump condenser. The

heat exchanger located in the preheating tank is connected via pipelines to the heat pump condenser. (Kovalev et al., 2015, Kovalev, 2014; Mikheeva et al., 2021).

In the heat pump condenser heat exchange takes place between the high-grade refrigerant and the prepared water, which is then sent to the heat exchanger located in the preheating tank, where heat exchange takes place between the prepared water and the influence, as a result of which the influence is heated to the operating temperature of the fermentation process and is alternately supplied to the blocks. modules. The heating system, including heat exchangers and pipelines, is filled with treated water. Treated water - water chemically softened with the help of complexones, used to prevent scale and ferrous deposits, as well as the formation of corrosion on the walls of pipelines and equipment. (Kovalev, 2013; Nikitina et al., 2021)

The aim of the work is to form the technological appearance of the system for preliminary preparation of the substrate for anaerobic digestion for the subsequent assessment of the possibility of maintaining the temperature regime in the digester on the basis of experimental data, as well as to develop the energy balance of the proposed scheme to determine the criteria for evaluating the proposed scheme.

MATERIALS AND METHODS

To achieve this goal, information research methods were used, including standard analytical methods of processing and analysis, as well as methods of a modern systematic approach. These methods form the basis for the study of waste disposal systems and their energy-saving technologies. Analytical studies were carried out on the basis of the well-known laws of heat engineering and thermodynamics. Also, the work used methods of processes and devices of chemical technology, methods of system analysis and mathematical modeling using the theoretical foundations of heat engineering, physical modeling and mathematical data processing.

Experimental Biogas Plant

The experimental plant was created with system of multiplicity substrate supply to the bioreactor. (Kovalev et al., 2020a)

The experimental plant is shown in Figure 2.

The experimental plant consists of a preheating tank -1, in which a mechanical paddle mixer -2 is mounted for hydrolysis of the influent and increasing the rate of heat exchange between the influent and the heat exchanger -3; bioreactor -4 with an internal heat exchanger -5 to maintain the temperature regime of fermentation and an unloading device -6, which is connected to the effluent settler -7. A heat exchanger -8 is mounted in the effluent settler to extract heat energy from the effluent. The heat exchanger -8 is connected by means of pipelines to the supply pump of the line “settler - heat pump” -9 and to the evaporator -10 of the heat pump -11. In the evaporator -10 of the heat pump -11, heat exchange takes place between the prepared water of the “settler - heat pump” line and the low-grade low-boiling refrigerant, which, after increasing the energy potential in the compressor -12 of the heat pump -11, is sent to the condenser -13 of the heat pump -11.

Heat exchanger -3 is connected via pipelines to the supply pump of the line “heat pump - preheating tank” -14 and to the condenser -13 of the heat pump -11.

In the condenser -13 of the heat pump -11, heat exchange takes place between the high-potential low-boiling refrigerant and the prepared water of the “heat pump - preheating tank” line, which is sent to the heat exchanger -3 with the help of the pump -14, where heat exchange takes place between the prepared water and the influence. Influent is heated to the operating temperature of the fermentation process and fed to bioreactor -4.

Experimental biogas plant: reactor working volume - 0.25 m³; reactor gas space - 0.01 m³; temperature regime - thermophilic - 55 ° C; instrumentation and control devices (flow meter, thermometer, resistance thermocouple, meter-regulator).

Figure 2. Technological diagram of an experimental biogas plant

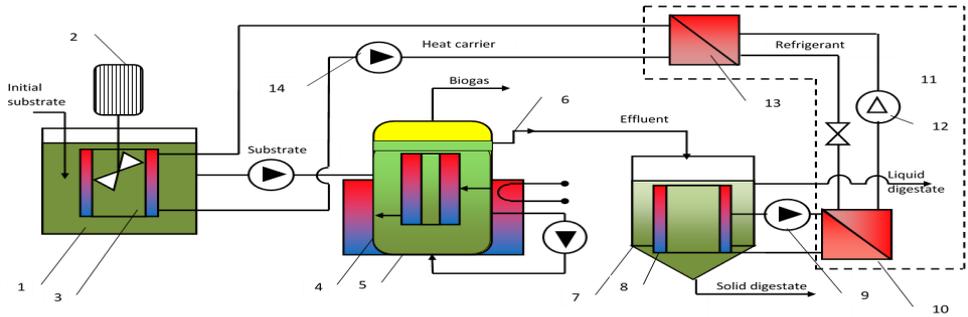


Figure 3. General view of the experimental setup



Heat pump: R717 refrigerant; compressor KF 130, compressor capacity 1 kW; evaporator, condenser and superheater - plate heat exchangers M12-50 GL GL.

Energy Balance of a Biogas Plant

Efficient energy production at a biogas plant, according to (Kovalev et al., 2020c) is possible only when the total energy of the produced biogas will significantly exceed the energy consumption for its production, ie. the condition must be met

$$\frac{V_{bg} * \lambda}{\left(\frac{E_{ON}}{\eta_e} + \frac{Q_{ON}}{\eta_H} \right) * 3600} \gg 1 \quad (1)$$

where: V_{bg} – total amount of produced biogas, m^3 / day ; λ – calorific value of biogas, kJ / m^3 ; E_{ON} – electricity consumption for own needs of the plant, kWh; η_e – efficiency converting biogas energy into electricity; Q_{ON} – heat consumption for own needs of the plant, kWh; η_H – efficiency converting biogas energy into thermal energy (Kovalev, 2014).

The amount of commercial (unused for the plant's own needs) biogas [m³ / day] can be presented as

$$V_{cbg} = V_{bg} - \frac{E_{ON} / \eta_e + Q_{ON} / \eta_H}{\lambda} * 3600 \quad (2)$$

Heat consumption for own needs of the biogas plant is:

$$Q_{ON} = Q_{init} + Q_{HLC} - Q_R \quad (3)$$

where: Q_{init} – energy consumption for preheating the substrate to the fermentation temperature, kWh; Q_{HLC} – daily energy consumption to compensate for heat loss from enclosing structures and pipelines, kWh; Q_R – amount of recovered energy, kWh.

Heat consumption for preheating the substrate [kWh] is defined as

$$Q_{init} = \frac{C_{init} * \rho_{init} * V_{init} * (t_{AP} - t_{init}) * n}{24 * 3600} \quad (4)$$

where: c_{init} – heat capacity of the substrate, kJ/(kg·K); ρ_{init} – substrate density, kg/m³; V_{init} – daily loading dose, m³/day; t_{AP} – final temperature of heating the substrate (fermentation temperature), °C; t_{init} – initial substrate temperature, °C; n – the number of operation hours of the heat pump per day, h/day.

Average daily heat consumption [kWh] required to compensate for heat losses through the enclosing surfaces of the bioreactor at the average annual outside air temperature

$$Q_{HLC} = k * F * (t_{AP} - t_o) * 10^{-3} * 24 \quad (5)$$

where: k – heat transfer coefficient, W/(m²·K); F – the area of the enclosing surfaces of the bioreactor, m²; t_{AP} – bioreactor substrate temperature (fermentation temperature), °C; t_o – outdoor temperature, °C.

Maximum daily amount of low-grade effluent heat [kW]:

$$Q_{eff}^{max} = \frac{C_{eff} * \rho_{eff} * V_{eff} * (t_{AP} - t_{C min}) * 10^{-3}}{24 * 3600} \quad (6)$$

where: $t_{C min}$ – effluent settler temperature required to stop residual gas evolution, °C.

Average daily amount of heat recovered [kWh]:

$$0 \leq Q_R < Q_{eff}^{max} * \left(\frac{\varepsilon}{\varepsilon - 1} \right) * n \quad (7)$$

where ε – conversion factor of the heat pump taking into account the isentropic and mechanical efficiency of the heat pump compressor.

MATHEMATICAL MODEL AND ALGORITHM FOR SELECTION OF PARAMETERS OF HEAT EXCHANGERS AND HEAT PUMP COMPRESSOR

The purpose of modeling the parameters of heat exchangers and a heat pump compressor of a heat supply system for biogas plants is to evaluate the parameters and operating conditions of heat exchangers and a compressor in relation to different temperature modes of operation of a biogas plant, daily loading rates and physical properties of the processed substrate and refrigerant.

Basic design dependencies:

$$\begin{cases} N_{comp} = f(P_i) \\ F_{HE\ PT} = f(P_j) \\ F_{HE\ SET} = f(P_k) \end{cases} \quad (8)$$

where: N_{comp} – compressor power, kW;

P_i – parameters for determining the compressor power;

$F_{HE\ PT}$ – heat exchanger area in the preheating tank, m²;

P_j – parameters for determining the area of the heat exchanger in the preheating tank;

$F_{HE\ SET}$ – area of the heat exchanger in the effluent settler, m²;

P_k – parameters for determining the area of the heat exchanger in the effluent settler.

The first main calculated dependence in this case will look like this:

$$P_i \ni \left((c; \rho; \nu; (P; t)^{crit})_{ref}; t_{AP}; V_{init}; t_{init}; (c; \rho; \nu)_{init}; V_R; G_{LP}; G_{HC1}; G_{HC2}; HE \right) \quad (9)$$

where: $(c; \rho; \nu; (P; t)^{crit})_{ref}$ – physical properties of the refrigerant, including heat capacity [kJ/(kg·K)], density [kg/m³], viscosity [m²/s], critical temperature [°C] and pressure [MPa];

t_{AP} – anaerobic process (fermentation) temperature, °C;

V_{init} – daily loading dose of bioreactor, m³/day;

t_{init} – initial substrate temperature, °C;

$(c; \rho; \nu)_{init}$ – physical properties of the substrate, including heat capacity [kJ/(kg·K)], density [kg/m³], viscosity [m²/s];

V_R – reactor volume, m³;

G_{LP} – loading pump feed, m³/h;

$G_{HC1}; G_{HC2}$ – supply of heating agent circulation pumps, m³/h;

HE – types of heat exchangers in the preheating tank and effluent settler.

$$V_{init} = f(t_{init}; V_R; TS_{init}; TVS_{init}) \quad (10)$$

$$(c; \rho; \nu)_{init} = f(TS_{init}) \quad (11)$$

$$G_{LP} = f(V_{init}) \quad (12)$$

$$G_{HC1} = f(d_1; Q_{init}; t_{AP}) \quad (13)$$

$$G_{HC2} = f(d_2; Q_C; t_{AP}) \quad (14)$$

at W_{opt} - the optimal speed in the pipeline equal to 1 m / s;

where: TS_{init} - total solids content of initial substrate, g/l;

TVS_{init} - total volatility solids (organic matter) content of initial substrate, g/l;

d_1 - diameter of the pipeline to the preheating tank heat exchanger, m;

Q_{init} - energy consumption for preheating the initial substrate to the fermentation temperature, W;

d_2 - diameter of the pipeline to the heat exchanger of the effluent settler, m;

Q_C - energy consumption taken from the effluent, W.

The second main calculated dependence in this case will look like this:

$$F_{HE PT} = \frac{Q_{init}}{k_{HE PT} * \Delta t_1} \quad (15)$$

where: $F_{HE PT}$ - preheating tank heat exchanger area, m²;

$k_{HE PT}$ - heat transfer coefficient of the preheating tank heat exchanger, W/(m²·K);

Δt_1 - average temperature head through the wall of the heat exchanger of the preheating tank, °C.

$$Q_{init} = f(V_{init}; t_{AP}; t_{init}) \quad (16)$$

where t_{init} - initial substrate temperature, °C.

$$\Delta t_1 = f(t_{AP}) \quad (17)$$

$$k_{HE PT} = f(G_{LP}; G_{HC1}; HE; (c; \rho; \nu)_{init}) \quad (18)$$

The third main calculated dependence in this case will look like:

$$F_{HE SET} = \frac{Q_C}{k_{HE SET} * \Delta t_2} \quad (19)$$

where: $F_{HE SET}$ - effluent settler heat exchanger area, m²;

$k_{HE SET}$ - heat transfer coefficient of the effluent settler heat exchanger, W/(m²·K);

Δt_2 - average temperature head through the wall of the effluent settler heat exchanger, °C.

$$Q_C = f(V_{init}; t_{AP}; t_C) \quad (20)$$

where t_c – temperature required to stop residual gas evolution, °C.

$$\Delta t_2 = f(t_{AP}) \quad (21)$$

$$k_{HE\ SET} = f(G_{HC2}; HE; (c; \rho; \nu)_{init}) \quad (22)$$

From the heat balance equations:

$$Q_C = Q_{init} - N_{comp} + Q_{HL1} + Q_{HL2} + Q_{HLC} \quad (23)$$

where: $Q_{HL1,2}$ – heat loss from pipelines to the environment, W;

Q_{HLC} – heat used to compensate for heat losses to the environment from the enclosing surfaces of the bioreactor, W.

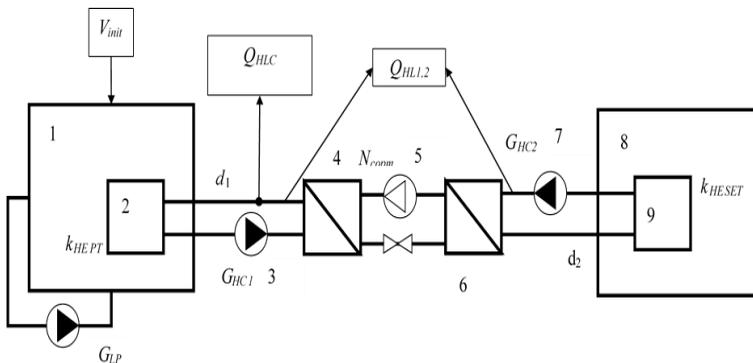
In the proposed scheme, in order to reduce operating costs for production, the type of heat exchanger for the preheating tank and settler is selected corresponding to the type of heat exchanger in a block-modular reactor - a coaxial heat exchanger.

In this case, the functions depending on the type of heat exchangers will take the following form:

$$\left\{ \begin{array}{l} N_{comp} = f\left(\left(c; \rho; \nu; (P; t)_{ref}^{crit}\right); V_{init}; t_{AP}; G_{LP}; G_{HC1}; G_{HC2}; (c; \rho; \nu)_{init}\right) \\ k_{HE\ PT} = f\left(G_{LP}; G_{HC1}; (c; \rho; \nu)_{init}\right) \\ k_{HE\ SET} = f\left(G_{HC2}; (c; \rho; \nu)_{init}\right) \end{array} \right. \quad (24)$$

The main calculated dependencies and their arguments are schematically shown in Figure 4.

Figure 4. Block diagram of the main calculated dependencies of the heat supply system with the recovery of waste heat of the effluent of a block-modular biogas plant



1 - preheating tank; 2 - heat exchanger in the preheating tank; 3 - heating medium circulation pump; 4 - condenser of the heat pump; 5 - heat pump compressor; 6 - heat pump evaporator; 7 - pump for circulation of the cooling coolant; 8 - effluent settler; 9 - heat exchanger in the effluent settler.

ALGORITHM FOR DETERMINING THE OPTIMAL PARAMETERS OF HEAT EXCHANGERS AND A HEAT PUMP COMPRESSOR

1. Input of initial data, including the following values: V_{init} ; n ; t_{AP} ; t_{init} ; t_C ; t_O .
2. Selection of V_{PT} and V_{SET} according to the following dependencies

$$V_{PT} = 1,3 * V_{init} * n \quad (25)$$

1,3 – an empirical coefficient taken from the condition of the duration of hydrolysis (12-24 hours) and the time of preliminary processing of the daily loading dose (operating time of the heat pump compressor), taken 24 hours / day.

$$V_{SET} = 1,5 * V_{init} * n \quad (26)$$

3. Calculation of Q_{init} , Q_C and Q_{HLC} values.
4. Calculation of G_{HC1} and G_{HC2} values.
5. Selection of d_1 and d_2 values at $W_{opt} = 1$ m/s.
6. Calculation of $F_{HE PT}$ value provided $(d; h)_{HE PT} < (d; h)_{PT}$.
7. Calculation of Q_{HL1} and Q_{HL2} values.
8. Calculation of $F_{HE SET}$ value provided $(d; h)_{HE SET} < (d; h)_{SET}$.
9. Calculation of heat loads on the evaporator and condenser from the heat balance equations:

Table 2. Rates of heating of the influent and of the cooling of the effluent

N ^o	$t_{eff st}, ^\circ C$	$W_{inf}^*, ^\circ C / \text{min}$	$W_{eff}^*, ^\circ C / \text{min}$	$t_{EV av}, ^\circ C$	$t_{CON av}, ^\circ C$	$W_{inf}^*, ^\circ C / (\text{m}^3 \cdot \text{min})$	$W_{eff}^*, ^\circ C / (\text{m}^3 \cdot \text{min})$
1	20	0.403	0.085	9	53	4.03	0.34
2	25	0.4556	0.098	11	50	4.556	0.392
3	30	0.4558	0.122	14	52	4.558	0.488
4	35	0.4541	0.142	14	49	4.541	0.568
5	40	0.4537	0.1648	15	52	4.537	0.659
6	45	0.4529	0.1868	15	54	4.529	0.747
7	50	0.4522	0.2088	16	56	4.522	0.835
8	55	0.4514	0.2308	17	60	4.514	0.923

$$Q_{EV} = Q_C + Q_{HL2} \quad (27)$$

$$Q_{EV} = Q_{CON} - N_{comp} \quad (28)$$

Figure 5. Rate of temperature change in the preheating tank and in the effluent settler

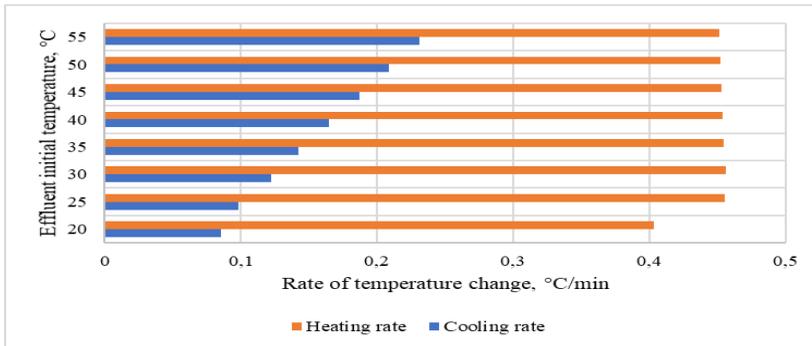


Figure 6. Ratio of specific heating and cooling rates

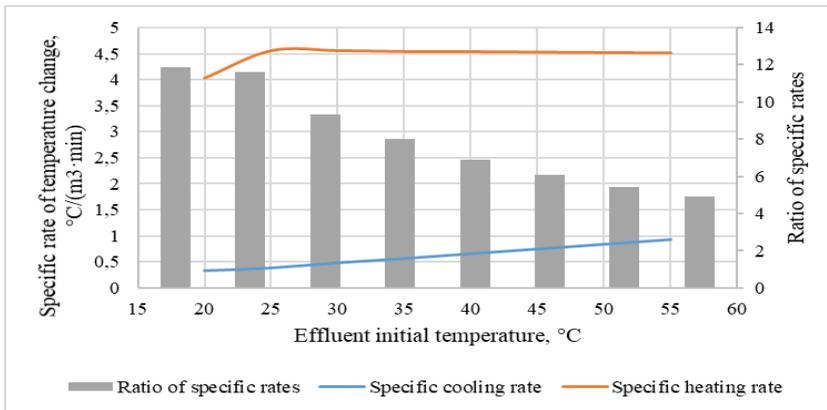
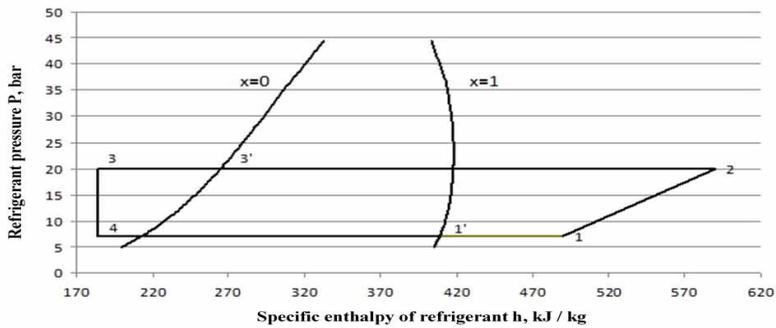


Figure 7. P-h diagram of the experimental plant heat pump operation



$$Q_{CON} = Q_{init} + Q_{HL1} + Q_{HLC} = N_{comp} + Q_C + Q_{HL2} \quad (29)$$

10. Checking d_1 and d_2 values.

It should be noted that the formulas of both the mathematical model and the algorithm are based on the laws of thermodynamics and heat engineering, as well as on the law of conservation of energy, therefore they can be used in the selection of equipment for both experimental and industrial biogas plants.

RESULTS AND DISCUSSION

According to the data obtained in the course of the experiment (temperatures of the influent and effluent), the rates of heating of the influent and of the cooling of the effluent were obtained. The calculation data are summarized in Table 2.

Figure 5 shows the dependence of the rate of temperature change in the preheating tank and in the effluent settler on the initial temperature of the effluent.

As can be seen from Figure 5, the highest rate of heating of the influence W_{inf} is observed at the initial temperature of the effluent t_{effst} the beginning of 30 ° C. The highest cooling rate of the effluent, W_{eff} , was obtained at the initial temperature of the effluent t_{effst} 55 ° C; however, this calculation does not take into account the heat loss from enclosing structures and pipelines, which will be greatest at a given initial temperature of the effluent.

Figure 6 shows the dependence of the specific rate of temperature change in the preheating tank and in the effluent settler as well as the dependence of their ratio on the initial temperature of the effluent.

Based on the initial data and data obtained in the course of experimental work, a P-h diagram of the heat pump operation process was built, shown in Figure 7.

Thus, the heat load in the evaporator q_{ev} is 225.3 kJ / kg; thermal load in the condenser $q_{con} = 325.3$ kJ / kg; thermal load in the superheater $q_{sh} = 81$ kJ / kg. Since the refrigerant flow rate is 0.01 kg / s, the power of the evaporator Q_{EV} is 2.253 kW; encoder power $Q_{CON} = 3.253$ kW; superheater power $Q_{SH} = 0.81$ kW. The conversion factor ϵ is 4.063.

The values of the heat load on the heat exchangers of the heat pump, the operating time of the heat pump, the heat conversion coefficients of the heat pump for each pair of the experiment are given in Table 3.

Table 3. Results of experiments on heat pump elements

	N°1-2	N°3-4	N°5-6	N°7-8	Average values
Heat load on the evaporator, kJ/kg	224.8	226.74	229.04	221.77	225.3
Heat load on the condenser, kJ/kg	324.8	326.74	329.04	321.77	325.3
Heat load on the superheater, kJ/kg	81	81	81	81	81
Heat pump conversion factor	4.058	4.077	4.1	4.028	4.063

The values of the heat transfer coefficients are practically constant in each experiment, since the dimensions and materials of the heat exchangers, as well as the flow rates of the heat carriers, did not change. However, with a change in the temperature of the coolants, their physical properties change, which affects the criterion dependences, and, as a consequence, the values of the heat transfer coefficients. The values of the heat transfer coefficients are given in Table 4.

Table 4. Heat transfer coefficients

	N°1-2	N°3-4	N°5-6	N°7-8	Average values
Internal of heater in the preheating tank, W/(m ² ·K)	887.7111	869.9271	878.1012	856.7088	872.822
External of heater in preheating tank, W/(m ² ·K)	678.6131	664.7334	671.6393	655.1459	667.2229
Internal of cooler in the settler, W/(m ² ·K)	284.8	295.62	314.34	326.74	304.93
External of cooler in the settler, W/(m ² ·K)	177.48	183.14	194.31	202.78	188.46

Table 5. The amount of low-grade effluent heat and recovered heat

	N°1-2	N°3-4	N°5-6	N°7-8	Average values
Maximum daily amount of effluent heat, Q_{eff}^{max} , kWh	0.293	0.224	0.336	0.266	0.28
The amount of recovered heat, Q_R , kWh	0.372	0.281	0.42	0.33	0.351
Estimated amount of recovered heat, kWh	0.391	0.299	0.448	0.354	0.373

Table 5 shows the amounts of low grade effluent heat, as well as the calculated amounts of recovered heat for each pair of experiments.

Based on the obtained experimental data and the developed energy balance, it is possible to determine the specific volumetric amount of energy stored in the commercial (not used for the biogas plant's own needs) biogas according to the following formula:

$$V_{cbg} = \frac{V_{bg} - E_{ON}}{V_R} \quad (30)$$

where: V_{cbg} – specific volumetric amount of energy stored in commercial biogas, kWh/(m³ reactor · day);

V_{bg} – the amount of energy stored in the produced biogas, kWh/day;

E_{ON} – the amount of energy consumed for own needs of the biogas plant, kWh/day;

V_R – reactor volume, m³.

Based on the obtained experimental data and formula (30), the use of the developed improved heat supply system of a biogas plant for the processing of bedding cattle manure with recovery of

the effluent heat using a compression heat pump makes it possible to obtain a specific volumetric amount of energy stored in the commercial (not used for the biogas plant's own needs) biogas in the amount of 5.6 kWh/(m³ reactor · day).

The resulting value is 40% more than when using a traditional anaerobic bioconversion system, taking into account all costs for own needs.

The obtained experimental data generally consistent with the data obtained by other authors. (Abusoglu et al., 2021; Blázquez et al., 2021; Holik et al., 2021; Sung et al., 2017; Weinand et al., 2019)

DIRECTION FOR FURTHER RESEARCH

Areas of further research include the use of various technological solutions to reduce the energy consumption for the own needs of biogas plants. These technological solutions include:

- division of the total volume of the anaerobic bioreactor to create optimal conditions for the vital activity of microorganisms of different stages;
- the use of energy-efficient methods of preliminary processing of the initial substrate;
- the use of various renewable energy sources, including solar energy converters (photovoltaic modules (Kharchenko et al., 2019; Panchenko, 2020; Panchenko et al., 2020), photovoltaic thermal modules (Panchenko et al., 2019; Panchenko, 2021), thermal modules), in combination with the process of anaerobic bioconversion.

CONCLUSION

The article assesses the possibility of using a compression heat pump in the heat supply system of a biogas plant to maintain the temperature regimes of an anaerobic bioreactor. According to the experiments carried out, as well as the developed energy balance, the use of a compression heat pump in the heat supply system of biogas plants for processing organic animal waste allows to:

1. Maintain a thermophilic temperature regime in an anaerobic bioreactor by recuperating the heat of the effluent using a heat pump.
2. Significantly reduce costs for own needs, which ultimately leads to a significant (40%) increase in the volume of commercial (not used to compensate for the biogas plant's own needs) biogas.
3. Ensure the independence of the plant for the processing of organic waste from animal husbandry from thermal and electrical networks of external sources of energy supply.
4. Increase the production of both heat and electric energy.

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REFERENCES

- Abusoglu, A., Tozlu, A., & Anvari-Moghaddam, A. (2021). District heating and electricity production based on biogas produced from municipal WWTPs in Turkey: A comprehensive case study. *Energy*, 223, 119904. doi:10.1016/j.energy.2021.119904
- Alqaralleh, R. M., Kennedy, K., & Delatolla, R. (2018). Improving biogas production from anaerobic co-digestion of thickened waste activated sludge (TWAS) and fat, oil and grease (FOG) using a dual-stage hyper-thermophilic/thermophilic semi-continuous reactor. *Journal of Environmental Management*, 217, 416–428. doi:10.1016/j.jenvman.2018.03.123 PMID:29627647
- Artamonov, A. V., Izmailov, A. Yu., Kozhevnikov, Yu. A., Kostyakova, Yu. Yu., Lobachevsky, Ya. P., Pashkin, S. V., & Marchenko, O. S. (2018). Effective purification of concentrated organic wastewater from agro-industrial enterprises, problems and methods of solution. *AMA. Agricultural Mechanization in Asia, Africa and Latin America*, 49, 49–53.
- Badmaev, Y.T. (2018). Improvement of anaerobic processing technology of pig breeding manufactures in the conditions of the republic of buryatia. *Theses of Candidate Dis.*
- Blázquez, C. S., Borge-Diez, D., Martín Nieto, I., Farfán Martín, A., & González-Aguilera, D. (2021). Multi-parametric evaluation of electrical, biogas and natural gas geothermal source heat pumps. *Renewable Energy*, 163, 1682–1691. doi:10.1016/j.renene.2020.10.080
- Carrillo-Reyes, J., Albarrán-Contreras, B. A., & Buitrón, G. (2019). Influence of added nutrients and substrate concentration in biohydrogen production from winery wastewaters coupled to methane production. *Applied Biochemistry and Biotechnology*, 187(1), 140–151. doi:10.1007/s12010-018-2812-5 PMID:29911268
- Chadwick, D., Sommer, S., Thorman, R., Fanguero, D., Cardenas, L., Amon, B., & Misselbrook, T. (2011). Manure management: Implications for greenhouse gas emissions. *Animal Feed Science and Technology*, 166–167, 514–531. doi:10.1016/j.anifeeds.2011.04.036
- Chen, Y., Rößler, B., Zielonka, S., Wonneberger, A.-M., & Lemmer, A. (2014). Effects of Organic Loading Rate on the Performance of a Pressurized Anaerobic Filter in Two-Phase Anaerobic Digestion. *Energies*, 7(2), 736–750. doi:10.3390/en7020736
- Edwards, J., Othman, M., & Burn, S. (2015). A review of policy drivers and barriers for the use of anaerobic digestion in Europe, the United States and Australia. *Renewable & Sustainable Energy Reviews*, 52, 815–828. doi:10.1016/j.rser.2015.07.112
- Elalami, D., Monlau, F., Carrere, H., Abdelouahdi, K., Oukarroum, A., Zeroual, Y., & Barakat, A. (2020). Effect of coupling alkaline pretreatment and sewage sludge co-digestion on methane production and fertilizer potential of digestate. *The Science of the Total Environment*, 743, 140670. doi:10.1016/j.scitotenv.2020.140670 PMID:32758825
- Gerber, P. J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., & Dijkman, J. (2013). Tackling climate change through livestock – a global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations (FAO).
- Holik, M., Živić, M., Virag, Z., Barac, A., Vujanović, M., & Avsec, J. (2021). Thermo-economic optimization of a Rankine cycle used for waste-heat recovery in biogas cogeneration plants. *Energy Conversion and Management*, 232, 1138–1197. doi:10.1016/j.enconman.2021.113897
- Ishikawa, S., Connell, N. O., Lechner, R., Hara, R., Kita, H., & Brautsch, M. (2021). Load response of biogas CHP systems in a power grid. *Renewable Energy*, 170, 12–26. doi:10.1016/j.renene.2021.01.120
- Izmaylov, A.Yu., Lobachevskiy, Ya.P., Fedotov, A.V., Grigoryev, V.S., & Tsench, Yu. S. (2018). Adsorption-Oxidation Technology of Wastewater Recycling in Agroindustrial Complex Enterprises. *Vestnik mordovskogo universiteta = Mordovia University Bulletin*, 28(2), 207–221. .10.15507/0236-2910.028.201802.207-221
- Kharchenko, V., Nikitin, V., Tikhonov, P., Panchenko, V., & Vasant, P. (2019). Evaluation of the Silicon Solar Cell Modules. *Advances in Intelligent Systems and Computing*, 866, 328–336. doi:10.1007/978-3-030-00979-3_34

- Kovalev, A., Kovalev, D., Panchenko, V., Kharchenko, V., & Vasant, P. (2020a). Optimization of the Process of Anaerobic Bioconversion of Liquid Organic Wastes. *Advances in Intelligent Systems and Computing*, 1072, 170–176. doi:10.1007/978-3-030-33585-4_17
- Kovalev, A., Kovalev, D., Panchenko, V., Kharchenko, V., & Vasant, P. (2020b). System of Optimization of the Combustion Process of Biogas for the Biogas Plant Heat Supply. *Advances in Intelligent Systems and Computing*, 1072, 361–368. doi:10.1007/978-3-030-33585-4_36
- Kovalev, A.A. (2014). Improving the energy efficiency of biogas plants [Povysheniye energeticheskoy effektivnosti biogazovyykh ustanovok]. *Theses of Candidate Dis.*
- Kovalev, A.A., Kovalev, D.A., & Grigoriev V.S. (2020c). Energy Efficiency of Pretreatment of Digester Synthetic Substrate in a Vortex Layer Apparatus. *Inzhenernyye tekhnologii i sistemy = Engineering Technologies and Systems*, 30(1), 92-110. .10.15507/2658-4123.030.202001.092-110
- Kovalev, A.A., Kovalev, D.A., & Kharchenko, V.V. (2013). Heating system for biogas plant of block-modular design using heat recovery of effluent for farms for 400 heads of cattle. *Alternative Energy and Ecology*, (5), 61-67.
- Kovalev, A.A., Kovalev, D.A., Litt, Yu. V., & Katraeva I.V. (2020d). Biohydrogen Production in the Two-Stage Process of Anaerobic Bioconversion of Organic Substance of Liquid Organic Waste with Recycle of Digester Effluent. *Alternative Energy and Ecology*, 7(18), 87-100. .10.15518/isjaee.2020.07-18.87-100
- Kovalev, A. A., Kovalev, D. A., Panchenko, V., & Kharchenko, V. (2021). Intellectualized Control System for Anaerobic Bioconversion of Liquid Organic Waste. *International Journal of Energy Optimization and Engineering*, 10(1), 56–81. doi:10.4018/IJEOE.2021010104
- Kovalev, D.A., Kovalev, A.A., Karaeva, Yu.V., & Trakhunova, I.A. (2015). Energy efficiency analysis of a biogas plant with heat recovery of waste effluent heat. *Alternative Energy and Ecology*, (5), 45-54. .10.15518/isjaee.2015.05.006
- Latha, K., Velraj, R., Shanmugam, P., & Sivanesan, S. (2019). Mixing strategies of high solids anaerobic co-digestion using food waste with sewage sludge for enhanced biogas production. *Journal of Cleaner Production*, 210, 388–400. doi:10.1016/j.jclepro.2018.10.219
- Liu, X., Chang, F., Wang, C., Jin, Z., Wu, J., Zuo, J., & Wang, K. (2018). Pyrolysis and subsequent direct combustion of pyrolytic gases for sewage sludge treatment in China. *Applied Thermal Engineering*, 128, 464–470. doi:10.1016/j.applthermaleng.2017.08.091
- Mikheeva, E. R., Katraeva, I. V., Kovalev, A. A., Kovalev, D. A., Nozhevnikova, A. N., Panchenko, V., Fiore, U., & Litt, Yu. V. (2021). The Start-Up of Continuous Biohydrogen Production from Cheese Whey: Comparison of Inoculum Pretreatment Methods and Reactors with Moving and Fixed Polyurethane Carriers. *Applied Sciences (Basel, Switzerland)*, 11(2), 510. doi:10.3390/app11020510
- Moral, R., Bustamante, M. A., Chadwick, D. R., Camp, V., & Misselbrook, T. H. (2012). N and C transformations in stored cattle farmyard manure, including direct estimates of N₂ emission. *Resources, Conservation and Recycling*, 63, 35–42. doi:10.1016/j.resconrec.2012.04.001
- Namsaraev, Z. B., Gotovtsev, P. M., Komova, A. V., & Vasilov, R. G. (2018a). Current status and potential of bioenergy in the Russian Federation. *Renewable & Sustainable Energy Reviews*, 81, 625–634. doi:10.1016/j.rser.2017.08.045
- Namsaraev, Z. B., Litt, Yu. V., & Nozhevnikova, A. N. (2018b). Analysis of the raw material potential for biogas production in the Russian Federation. *Journal of Physics: Conference Series*, 1111(1), 012012. doi:10.1088/1742-6596/1111/1/012012
- Nikitina, A. A., Ermoshin, A. A., Zhuravleva, E. A., Kovalev, A. A., Kovalev, D. A., Panchenko, V., & Litt, Yu. V. (2021). Application of Polyacrylamide Flocculant for Stabilization of Anaerobic Digestion under Conditions of Excessive Accumulation of Volatile Fatty Acids. *Applied Sciences (Basel, Switzerland)*, 11(1), 100. doi:10.3390/app11010100
- Nozhevnikova, A. N., Kallistova, A. Yu., Litt, Yu. V., & Kevbrina, M. V. (2016). Biotekhnologiya i mikrobiologiya anaerobnoy pererabotki organicheskikh kommunal'nyh othodov [Biotechnology and microbiology of anaerobic processing of organic municipal waste]. *Universitetskaya kniga*.

- Panchenko, V. (2020). Roofing Solar Panels of Planar and Concentrator Designs. *International Journal of Energy Optimization and Engineering*, 9(4), 20–40. doi:10.4018/IJEOE.2020100102
- Panchenko, V. (2021). Photovoltaic Thermal Module With Paraboloid Type Solar Concentrators. *International Journal of Energy Optimization and Engineering*, 10(2), 1–23. doi:10.4018/IJEOE.2021040101
- Panchenko, V., Izmailov, A., Kharchenko, V., & Lobachevskiy, Ya. (2020). Photovoltaic Solar Modules of Different Types and Designs for Energy Supply. *International Journal of Energy Optimization and Engineering*, 9(2), 74–94. doi:10.4018/IJEOE.2020040106
- Panchenko, V., Kharchenko, V., & Vasant, P. (2019). Modeling of Solar Photovoltaic Thermal Modules. *Advances in Intelligent Systems and Computing*, 866, 108–116. doi:10.1007/978-3-030-00979-3_11
- Siddiqui, S., Zerhusen, B., Zehetmeier, M., & Effenberger, M. (2020). Distribution of specific greenhouse gas emissions from combined heat-and-power production in agricultural biogas plants. *Biomass and Bioenergy*, 133, 105443. doi:10.1016/j.biombioe.2019.105443
- Smith, J. U., Fischer, A., Hallett, P. D., Homans, H. Y., Smith, P., Abdul-Salam, Y., Emmerling, H. H., & Phimister, E. (2015). Sustainable use of organic resources for bioenergy, food and water provision in rural sub-Saharan Africa. *Renewable & Sustainable Energy Reviews*, 50, 903–917. doi:10.1016/j.rser.2015.04.071
- Sung, T., Kim, S., & Kim, K. C. (2017). Thermoeconomic analysis of a biogas-fueled micro-gas turbine with a bottoming organic Rankine cycle for a sewage sludge and food waste treatment plant in the Republic of Korea. *Applied Thermal Engineering*, 127, 963–974. doi:10.1016/j.applthermaleng.2017.08.106
- Weinand, J. M., McKenna, R., Karner, K., Braun, L., & Herbes, C. (2019). Assessing the potential contribution of excess heat from biogas plants towards decarbonising residential heating. *Journal of Cleaner Production*, 238, 117756. doi:10.1016/j.jclepro.2019.117756