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Analysis of technological schemes for biogas production using a heat pump

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ABSTRACT: Alternative way of increasing the energy efficiency of biogas energy utilization technology is considered. The article presents the main dependencies of the energy balance of installations for anaerobic processing of organic substrates. The technological scheme and the operating procedure of the manure wastewater treatment system based on their anaerobic-aerobic treatment using a compression heat pump in the heat supply system of the anaerobic digestion plant are shown. Graphs of dependences of efficiency of biogas installation with heat pump on optimal values of main parameters are calculated

KEY WORDS: compression heat pump, biogas plant, heat recovery, aerobic treatment of manure

I.INTRODUCTION

Despite the positive aspects of anaerobic processing of organic waste, it has a significant drawback - to ensure the temperature regime in a biogas installation (BGI), a significant amount of generated biogas (up to 60%) is required.
One of the ways to increase the energy efficiency of biogas plants is the use of heat pumps to recover the heat of the original manure in the heat supply system [1,2].
All produced biogas is used in the internal combustion engine (ICE) to drive the blower of the aeration tank and the heat pump compressor.
The heat from the heat recovery unit from the internal combustion engine during the winter period (from December to February inclusive) is used to compensate for heat losses through the enclosing surfaces of the digester (the compression heat pump operates only to preheat the substrate in the digester reactor), and in the summer period - for the needs of consumers [3.4].

II. DESCRIPTION OF SCHEME

The scheme of the manure treatment BGI system by using a heat pump is shown in Figure 1.
The sewage treatment system consists of a preheating tank in which a heat exchanger is mounted; an anaerobic digester with an internal heat exchanger to maintain the temperature regime of digestion and unloading devices that are connected to the initial manure sump. A heat exchanger is installed in the initial manure sump to extract thermal energy from it. The clarified fraction from the initial manure sump enters the aeration tank for subsequent treatment, and then to the sump. In the settler, the clarified fraction after aeration is separated into a purified liquid and excess sludge [5], which is sent to a preheating tank and, after mixing with the original substrate, is sent to an anaerobic reactor.
The heat exchanger, located in the initial manure sump, is connected by pipelines to the heat pump evaporator. In the heat pump evaporator, heat exchange occurs between the treated water and the low-grade refrigerant, which, after increasing the energy potential in the heat pump compressor, is sent to the heat pump condenser [6]. The heat exchanger located in the preheating tank is connected to the heat pump condenser via pipelines.
In the heat pump condenser, heat exchange takes place between the high-potential refrigerant and treated water [7], which is then sent to a heat exchanger located in the preheating tank, where heat exchange takes place between the treated water and the resulting substrate after the release of biogas, as a result of which the substrate is heated to the operating temperature of the process digestion and fed into an anaerobic digester [8,9].
All produced biogas is used in the internal combustion engine to drive the aerotank blower and the heat pump compressor [10,11].

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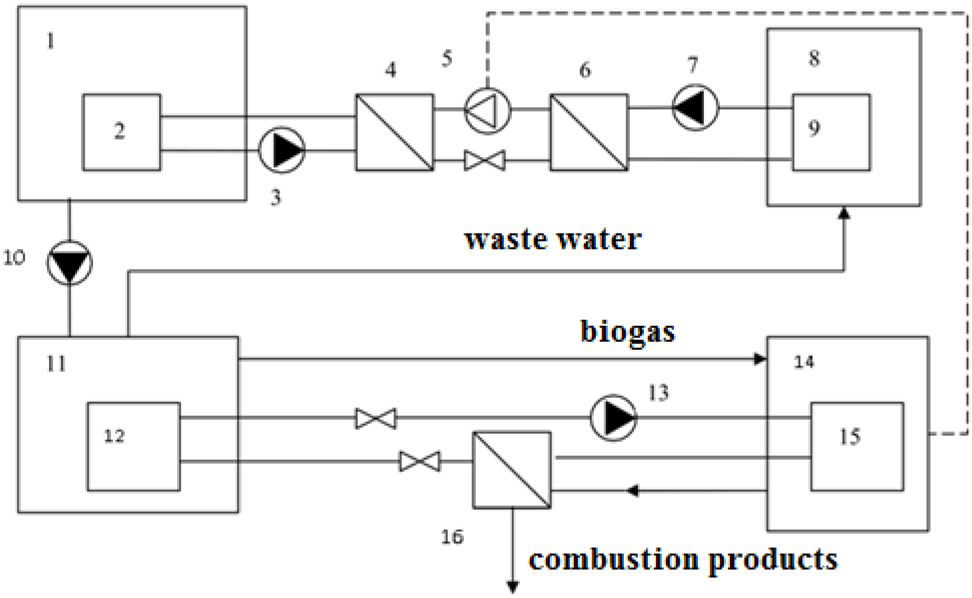

Fig.1 Technological scheme of the manure treatment system included BGI with heat pump:
1 - preheating tanks; 2 - heater in the tank; 3 - circulation pump; 4 - heat pump condensers; 5 - heat pump compressors; 6 - heat pump evaporators; 7 - water circulation pump; 8 - wastewater tank; 9 - heat exchanger in the waste water tank; 10 – manures pump; 11 - digester; 12 - heat recovery in the decomposition device; 14 - internal combustion engine; 15 - radiator for cooling the internal combustion engine; 16 - economizer

III. METHODOLOGY

A. Survey of publications

The main apparatus of the circuit is a digester, so we will give a detailed calculation of its thermal efficiency. To do this, we determine the surface area of the digester with a flat coating [12]:

$$S_p = 2\pi r \cdot h + \pi r^2 \quad (1)$$

here r is the digester radius (r=3.5 m); h - digester height (h =7.5 m)
The coefficient of heat transfer of the substrate to air k_ρ = 0.2 W/(m^2·K) and the heat capacity of the substrate c_ρ = 4098 J/(kg·K) were established. The indicator of the rate of cooling of the organic substrate m [13].

$$m = S_\rho k_\rho \tau_\rho / G_\rho \, c_\rho \quad (2)$$

here G_ρ is the mass of the substrate in the digester (G_ρ = 250,000 kg); τ_p is the duration of substrate heating in the digester (τ_ρ = 864,000 seconds), $t_{a.av}$ − average value of ambient temperature, t'' − required temperature in digester.
Approximate temperature of substrate in the digester is calculate

$$t_x = t_{a.av} + (t'' - t_{a.av})/exp(m) \quad (3)$$

The amount of heat required to heat the substrate from t_x to t'' (kJ) [12]:

$$Q_{heating}^{degister} = G_p c_p (t_c'' - t_x) 10^{-3} \quad (5)$$

Time required for heating substrate from the initial temperature to the required temperature in the digester [14], seconds:

$$\tau_{heating} = \frac{Q_{heating}^{degister}}{(i_w^{70} - i_w^{50}) g_{water} - q_{loss}} \quad (3)$$

here g_{water} is the consumption of network water in the digester heater (g_{water} = 1.1 kg/s for a traditional biogas plant; g_{water} = 0.23 kg/s for a biogas plant with heat recovery) [15]; i_w^{70} - enthalpy of network water (at t_w = 70°C i_w^{70}=293 kJ/kg); i_w^{50} - enthalpy of network water (at $t_w = 50$°C i_w^{50}= 209.6 kJ/kg) [12].
When the substrate is heated, we determine the average amount of heat transferred to it per unit time [16], kW:

$$q_{heat1} = \frac{Q_{heating}^{degister}}{\tau_{heating}} + q_{loss} \quad (4)$$

Thermal efficiency of the degister [17]:

$$\eta_{degister} = \frac{(q_{heat1} - q_{loss})}{q_{heat1}} \quad (5)$$

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In the traditional scheme, the overall thermal efficiency is equal to the fermentation efficiency [18].
The thermal efficiency of a biogas plant with the utilization of waste heat is determined by the following formula [19]:

$$\eta = \frac{Q_{BGI}}{Q_{sub}+Q_{ec}} \tag{6}$$

here Q_{BGI} is the heat input to the boiler with waste water, kW; Q_{sub} is the heat introduced by the heated substrate from the preheating tank, kW; Q_{ec}- heat supplied with hot water from the economizer of ICE, kW.
In a biogas plant, heat recovery, heating of network water, cooling of combustion products and utilization of the heat of the original manure by heat pump rich a positive technological effect.

B. Calculation of the characteristics of condensation heat exchangers

The modeling of the technical parameters of a cogeneration heat pump machine, which can be used to produce hot water by converting the heat released during cooling of the generated landfill biogas in order to dry it, was carried out in the following range of operating parameters:

- the final temperature of the cooled biogas is 15^0C;
- the temperature of the biogas supplied for drying was varied in the range of (25÷40) ^{0}C;
- the boiling point of the working fluid in the evaporator is 0°C; this value is related to the final temperature of the cooled biogas and the economically justified choice of the minimum temperature difference in the evaporator (15^0C), since the heat exchange in the evaporator takes place between the boiling liquid refrigerant on one side and the gas on;
- the condensation temperature took two values - 65 and 95^0C, which from below and from above limit the area that is economically feasible for district heating.

An economically justified minimum temperature difference in the condenser, equal to 5^0C, was chosen, since in the condenser heat exchange takes place between the condensing refrigerant vapor, on the one hand, and water, on the other. The lower value of the condensation temperature is focused on obtaining the minimum acceptable temperature of hot water (60 ^{0}C) and was 65 ^{0}C, and the upper value, which allows obtaining a hot water temperature of 90^0C, was limited by the level of compression pressure acceptable from technical and thermodynamic points of view, which increases significantly with increasing dew point temperature. Refrigerant R12, for example, at a temperature of 95^0C has a saturated vapor pressure of ~ 3 MPa, and at 0^0C ~ 0.3 MPa.
Some results of the performed calculations are presented graphically in Figures 2 and 3, which show a regular increase in the heat output and power consumption of the heat pump with an increase in the temperature of the biogas from manure.

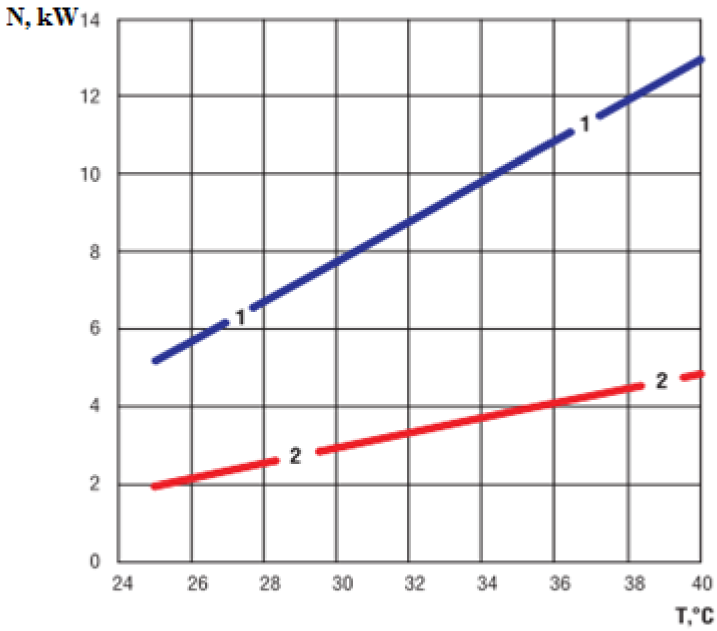

Fig.2 Graphs of dependence of useful power on the compressor drive shaft of heat pump on biogas temperature: graph -1-1- corresponds to the condensation temperature T_2=95^0C; graph -2-2- corresponds to the condensation temperature T_2=65^0C

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IV. RESULTS OF CALCULATIONS

The increase in power and heat output becomes more intense with an increase in the condensing temperature. It should be noted that the technical parameters at a temperature of condensation of the working fluid in the range from 65 to 95^{0}C are in the range of values enclosed on the presented graphs in the area between the curves shown. The upper lines on both graphs correspond to a dew point of 95^{0}C, and the lower curves correspond to a dew point of 65^{0}C. These condensation temperatures correspond to the following hot water temperatures: 60 and 90^{0}C.

The heat output of the heat pump in the range of operating parameters varies from 5 to 21 kW. The amount of hot water produced is from 100 to 400 l/h. The volumetric performance of the heat pump compressor, which determines the weight and size parameters of the machine, ranges from 20 to 100 m^3/h in the range of operating parameters. The drive power of the compressor unit is in the range from 2 to 13 kW [20].

The calculated technical parameters of the heat pump unit for the projected landfill correspond to the parameters of standard small steam chillers, which makes it possible to select commercially available equipment during the technical implementation of the project. The results of the performed simulation also substantiate the possibility of implementing energy efficient heat pump heating in the studied range of modes, provided that the project for utilizing the calorific value of biogas in a power combined-cycle power plant with high efficiency values is implemented.

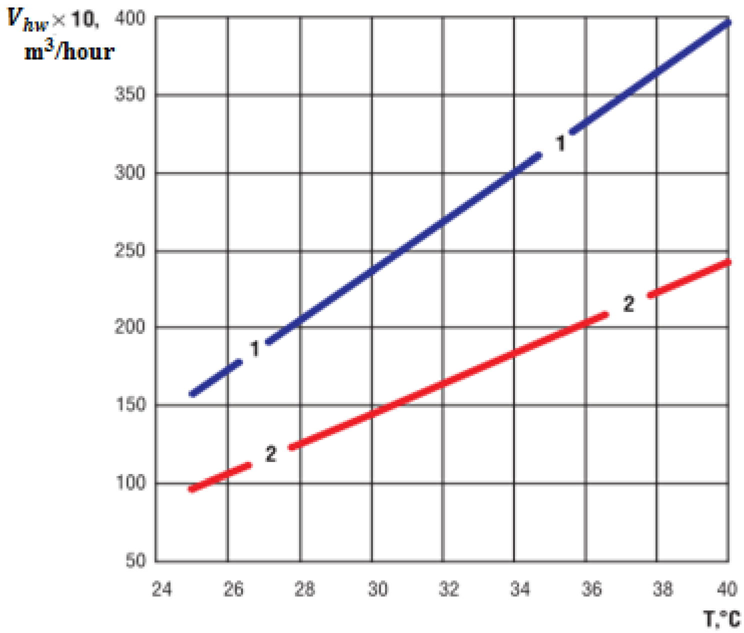

Fig.3 Heat pump performance curves for hot water volumes from biogas temperature:
graph -1-1- corresponds to the condensation temperature T_2=95^{0}C;
graph -2-2- corresponds to the condensation temperature T_2=65^{0}C

Some directions for improving the energy efficiency of the scheme under consideration may be of some interest, for example, the compressor can be driven directly using a gas ICE or GTU. You can also note the high effect of the use of alternative renewable energy sources, for example, wind power plants, which fully fits into modern concepts for the development of alternative energy.

V. CONCLUSION

In order to improve the energy efficiency of a biogas installation, a technological scheme for the utilization of waste heat by a heat pump has been proposed, which makes it possible to use biogas plants in regions with a low average annual ambient temperature.

The thermal efficiency of a traditional biogas installation is 39%, and that of a biogas plant with waste heat recovery by heat pump is 46%. It should be noted that the use of secondary energy resources in the production of biogas makes it possible to fully cover their energy needs in heat during the cold season.

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