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HARDWARE-CIRCUIT SOLUTIONS FOR THE IMPROVEMENT OF BIOGAS INSTALLATION EFFICIENCY

Heat exchangers for heat recovery of the used mixture in the system of biogas installation are analyzed, applying experimental-calculation method, their expedient constructions and operation modes are determined.

Key words: *bioconversion, heat-exchange in organic mixtures, forced convection, free convection, heat exchange modes, criterial equation, experimental-calculation method.*

Introduction

Each enterprise, where there is waste of organic origin has to solve problems of waste utilization. Anaerobic processing of waste in biogas installations (BGI) is one of the most promising methods of recovery, as a result of the application of this method we obtain ecological, energy and economic effects. In [1, 2] structural diagrams of BGI with used mixture heat recovery and biogas heat recovery are suggested, energy efficiency of these installations is analyzed. It is determined that as a result of the heat recovery the output of marketable biogas can be increased to 70…80% of the volume of the produced gas. But in this case, metal consumption of BGI will increase by 10…25 %.

The given paper is a continuation of the publications [3 – 10] and its aim is to apply experimental-calculation method (ECM) in design calculation and numerical experiment of used mixture heat recovery units in BGI system and determine their expedient constructions and operation modes.

Main results

We will consider the BGI [1, 2], where the heat recovery is realized in two directions: recovery of the used mixture heat (principle part of the recovered heat) and the recovery of the obtained biogas heat. The constructions of heat-exchangers-heat recovery units , are shown in Fig. 1. For the recovery of the used mixture heat additional expenses are needed for heat recovery unit and electric energy expenditures for the electric drive of the mixer. Thus, application of the recovery on one hand leads to increase of marketable biogas output, but on the other hand, it leads to the increase of metal consumption of the installation and electric energy consumption .

In such circuits it is important to design rationally heat exchangers-recovery units. Design and test calculations for the mixtures with limited information regarding thermal physical properties can be performed using experimental-calculation method [6, 8].

As the example, we will consider the circuit of BGI with active volume of the reactor $V_r = 20$ m^3, with two variants of heat recovery units (Fig. 1a, 1b).

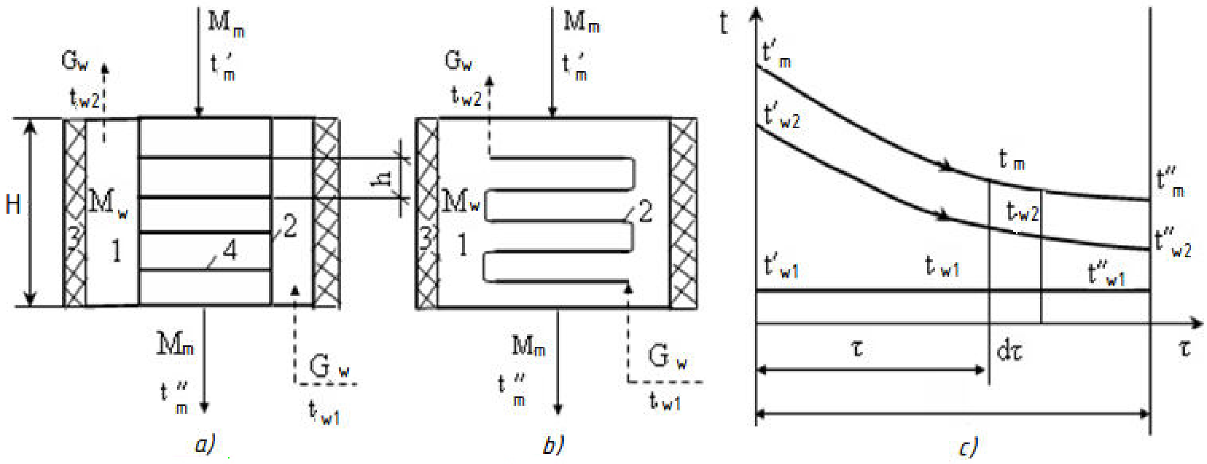

Fig. 1. Schematic structural diagram of the recovery unit: a) heat recovery unit with cylindrical surface of heat transfer; b) heat-recovery unit with coiled surface of heat exchange: 1 – external cylindrical vessel; 2 – heat exchange surface; 3 – insulation; 4 – steps; b) change of mixture and water temperatures in time in the recovery unit

Heat recovery unit of H height (Fig. 1a) is manufactured in such a way that working cavities are formed: internal cylindrical one with the volume V and external in the form of annular space. On the internal heat-exchanging surface of the cylindrical form the steps are located on the circle; they limit the development of heating and hydrodynamic boundary layer. Heat exchanger operates in semi flow mode. Warm (hot) mixture from the reactor during the loading enters the external vessel 1, fills it and remains in it until the next load/unloading operation of the reactor $\tau_{l\text{-}unl}$. During this period the mixture is cooled by the running water from the temperature in the reactor t_m' to certain final temperature t_m'' across heat exchanging surface 2. That is, the heat of the mixture is transferred to the water and is introduced into heat circuit of BGI. In the given case, the heat exchange in the internal and external vessels occurs under conditions of natural convection.

In heat recovery unit (Fig. 1b) the heated water moves in the tube and the mixture in the outside of tubes space is held during the time $\tau_{unl\text{-}l}$. Constant motion of mixture takes place in outside of tubes space relatively the tubes due to the mixer that rotates with constant angular speed. Linear velocity of the mixture relatively tubes according to biotechnological requirements does not exceed 0.6 m/sec. At such heat recovery unit circuit the heat exchange to water and in outside of tubes space is realized by means of forced convection. According to the results of our research it is determined that for heat exchange calculation in the substrates (mixtures) flows and in large volume in case of parallel flow of heat exchange surface by the mixture (Fig. 1b) one and the same already known criterial dependence can be used [6, 7].

We think that the water in heat recovery units (Fig. 1a and 1b) enters during the cycle $\tau_{unl\text{-}l}$ at constant temperature t_{w1} and leaves with the temperature t_{w2}, that changes in time. Quality picture of mixture and water temperatures change is shown in Fig. 1c. Temperatures at the beginning of the cooling process, in the process and at the end of the process are shown in Fig. 1c correspondingly: t_m', t_m, t_m'' - temperature of the mixture; t_{w1}', t_{w1}, t_{w1}'' - temperature of the water at the input into the recovery unit; t_{w2}', t_{w2}, t_{w2}'' - temperature of the water at the output from the heat recovery unit. Characteristic feature of such non-stationary heat exchange is that with the time the temperatures of non-flowing heat carrier (mixture) and heating running carrier (water), decrease.

Heat transfer and thermal balance equations for the total heat exchange surface F during the time interval $d\tau$ has the form

$$dQ = k \cdot F \cdot \overline{\Delta t} \cdot d\tau = G_w \cdot C_w \cdot (t_{w1} - t_{w2}) d\tau = M_m \cdot C_m \cdot dt_m , \qquad (1)$$

where $\overline{\Delta t}$ – is average difference of temperatures between the heat carriers at the moment of time τ; dt_m – is the value of mixture temperature change during time $d\tau$; k – is heat transfer coefficient from the mixture across the surface F to the water at the moment of time τ; C_w, C_m – thermal capacity of the water and the mixture at the moment of time τ; M_m – mass of the mixture in the annular space (Fig. 2a) of the cylindrical vessel (Fig. 2b) of heat recovery unite; $M_m = \rho_m \cdot V_{RU}$.

Temperature drop Δt at the moment of time τ is calculated as the log mean temperature difference

$$\overline{\Delta t} = \frac{t_{w2} - t_{w1}}{ln\dfrac{t_m - t_{w_1}}{t_m - t_{w_2}}}. \qquad (2)$$

In. dependences after corresponding transformations (1) and integration in the range from t_m' to t_m and t_{w1} to t_{w2} we have

$$\begin{cases} t_m = t_{w1} + \left(t_m' - t_{w1}\right) exp\left\{\dfrac{G_в C_w}{M_c C_m} \cdot \left[-1 + exp\left(-\dfrac{k \cdot F}{G_w C_w}\right)\right] \cdot \tau\right\}, \\ t_{w2} = t_m - \left(t_m - t_{w1}\right) exp\left(-\dfrac{kF}{G_w C_w}\right); \end{cases}, \qquad (3)$$

$$\begin{cases} t_m'' = t_{w1} + \left(t_m' - t_{w1}\right) exp\left\{\dfrac{G_w C_w}{M_c C_m} \cdot \left[-1 + exp\left(-\dfrac{k \cdot F}{G_w C_w}\right)\right] \cdot \tau_{l-unl}\right\}, \\ t_{w2}'' = t_m'' - \left(t_m'' - t_{w1}\right) exp\left(-\dfrac{kF}{G_w C_w}\right) \end{cases}. \qquad (4)$$

In the dependences (1) and (2): C_w – is average thermal capacity of the water in the range of temperatures $(t_{w1} \ldots t_{w2})$ and $(t_{w1} \ldots t_{w2}'')$; C_m – is average thermal capacity of the mixture in the range of temperatures $(t_m' \ldots t_m)$ and $(t_m' \ldots t_m'')$; k – is heat transfer coefficient averaged on the heat transfer surface F and correspondingly during the time τ_{l-unl}.

$$k = \psi_d \left(\frac{1}{\alpha_1} + \frac{\delta_{wal}}{\lambda_{wal}} + \frac{1}{\alpha_2}\right)^{-1}, \qquad (5)$$

where α_1 – is heat-transfer coefficient from the mixture to the surface of heat exchange averaged on the surface of heat exchange and correspondingly during the time τ_{l-unl} and temperatures range $(t_m' \ldots t_m)$ and $(t_m' \ldots t_m'')$; α_2 – is heat-transfer coefficient from the surface of heat exchange to water, being heated, averaged on the surface of heat exchange and correspondingly, during the time τ_{l-unl} and temperatures range $(t_{w1} \ldots t_{w2})$ and $(t_{w1} \ldots t_{w2}'')$; δ_{wal}, λ_{wal} – is the thickness of the wall, heat conductivity of wall material correspondingly ; ψ_d – decrease factor of heat transfer coefficient as a result of heat exchange surface pollution.

For determination of the heat transfer coefficient from heat exchange surface to water α_2 in various heat exchange modes methodical recommendations and reliable dependences are sufficient. Problems arise in case of determination of heat exchange intensity between the heat exchange surface and the mixture with limited information about thermophysical properties.

For this case we suggest the original experimental-calculation method, that contains rather simple but substantiated experimental part and simple calculation part.

Characteristic features of experimental-calculation method, applied in the given research, are the following:

- in the input data, if ECM is used, besides the list of single-valued conditions, natural samples of mixture, used as heat carries in heat recovery units being designed (thermal physical properties are assessed approximately), and their temperatures change in heat recovery unit must be presented;
- for each specimen of the mixture in the acceptable range of mixture temperatures change and thus, at average temperature of the mixture in heat exchange cycle, we determine at basic experimental stand the heat exchange coefficient between the mixture and heat exchange surface;
- applying the criterial dependences, corresponding to heat exchange mode (probable heat exchange mode is evaluated according to the technique, suggested by us) and using α_1 value, the complex of physical properties CPP_B^{exp}, that corresponds to basic heat exchange mode is determined;
- using CPP_B^{exp} value we determine the correction $C_{sear(B)}$, that corresponds to heat exchange mode in the equipment, being designed (probable heat exchanger mode is evaluated, applying the technique) on the given mixture;
- the complex of physical properties CPP_{sear}, that corresponds to the given fluid (suggested specimen of the fluid) and heat exchange mode in heat recovery unit, being designed is determined;
- applying the stucturized criterial equation that describes heat exchange mode in heat recovery unit, being designed, surface heat-transfer coefficient α_1 between the mixture and the wall in accordance with certain conditions of heat exchange is determined.

When using the systems of equations (1) and (2) we need the information, regarding the average values of C_m and ρ_m in the range of temperatures of the mixture in heat recovery unit, being designed. The given values with sufficient accuracy can be determined at the basic experimental stand [6, 8]: ρ_m – by weighting on the scales; C_m – from heat balances in the process of heat transfer from the water to the mixture, evaluating heat losses in the environment.

Heat recovery unit is designed according to functional diagram (Fig. 1). We will consider three variants of heat transfer: 1 – from water to water; 2 – from the chicken manure to the water; 3 – from the mixture of cattle and pigs substrates (ratio 1:1) to the water.

For the first two mixtures physical properties are known, and for the mixture of the substrates – are unknown. We will determine the surfaces of the heat exchange and parameters of heat exchange, applying experimental calculation method.

Initial data for heat recovery unit calculation:

Schematic structural diagrams of the unit are presented in Fig. 1.

Natural samples of mixtures for using experimental calculation method(ECM): chicken manure, mixture of cattle and pigs substrates (ratio 1:1).

Mixtures, loaded in cylindrical vessel 1 have the following initial data:

- humidity of the mixture - $W = 90\%$;
- time of mixture allowance in heat recovery unit - $\tau_{l\text{-}unil} = 6$ hrs;
- temperature of the mixture at the moment of loading in the heat recovery unit - $t_m' = 35$ °C;
- temperature of the mixture at the moment of unloading from the heat recovery unit - $t_m'' = 20$ °C.

Temperature of the water at the input into heat recovery unit in winter - $t_w' = 5$ °C.

Mass of water, chicken manure and the mixture of the substrate, loaded into the vessel 1, is $M_m = \rho_m \cdot V_{hu} = 498;\ 465;\ 512$ kg, correspondingly.

For schematic structural diagram in Fig. 1a:

- heat carrier rate across cylindrical vessel – $G_w = 0.03$ kg/s;
- typical size of heat exchange surface 2 – distance between the steps $h = 0.2$ m.

For schematic structural diagram in Fig. 1b:

- heat carrier rate across the coil-pipe - $G_w = 0.03$ kg/s;
- typical size of heat exchange surface 2 – diameter of coil pipe $d_{cl} = 25$ mm.

Diameter and height of the external vessel is $D = 200$ mm, $h = 120$ mm, dimensions of the internal vessel – d_1 = 96 mm, h_1 = 88 mm, thickness of the wall of the internal vessel – δ_{wal} = 0.5 mm; calculated interval of mixture temperatures t_m = 20…35 °C. The results of design calculation are given in Table 1.

Table 1

Results of the design calculation of semi- flow coaxial recovery unit (Fig. 1a) and with coiled heat exchange surface (Fig. 1b)

Heat exchange between	Free convection (FC)						Forced convection (FrC)		
	Calculated CPH*			CPH to be realized			Calculated and CP to be realized		
	F_{fc}	D_{fc}	H_{fc}	F'	D'	H'	F_{frc}	d_{frc}	L_{frc}
water - water	0,59	3,4	0,06	2,51	0,8	1,0	0,31	0,02	4,9
Chicken manure - water	0,87	2,3	0,12	2,51	0,8	1,0	0,35	0,02	5,6
mixture of the substrates of cattle +pigs - water	2,02	1,0	0,65	2,51	0,8	1,0	0,48	0,02	7,6

*CPH – constructive parameters of heat exchanger (CPH).

In the Table: F_{fc}, F_{frc} –are heat exchange surfaces in conditions of free (Fig. 1a) and forced convection of the mixture correspondingly (Fig. 1b); D_{fc}, D' – is the diameter of the internal cylindrical vessel; H_{fc}, H' –is the height of the internal cylindrical vessel; d_{frc}, L_{frc} –is the internal diameter and total length of pipes of coiled heat exchange surface, correspondingly. In the Table the numerical values of D_{fc} and H_{fc} are defined from the simultaneous solution of two equations $V_{my} = [(\pi \cdot D^2)/4]\cdot H_{fc}$ and $F_{fc} = \pi D_{fc}\cdot H_{fc}$.

There exists obligatory requirement to heat recovery unit of different constructions: volume of heat exchanger V_{hru}, filled with the used substrate, is determined depending on the volume of the reactor $V_{hru} = \psi \cdot V_r$, where ψ depends on the technological schedule of BGU loading -unloading. By the results of our analysis it is revealed that for semi-flow coaxial heat exchanger (Fig. 1a) calculated ratios D/H are not constructive for realization and the areas of heat exchange surfaces must be increased. This, in its turn, will lead to the increase of metal consumption. Numerical values of D', H', F' are obtained in case of rigid observation of $V_{hru} = \psi\cdot V_r$ and expedient height of heat recovery unit.

Fig. 2 shows the dependences of the areas of coiled heat exchanger and the temperature of the water at the output of heat recovery unit, calculated using experimental calculation method. Thus, the application of ECM enables to select the surface of heat exchanger-heat recovery unit, that will meet technological need in water with the preset temperature.

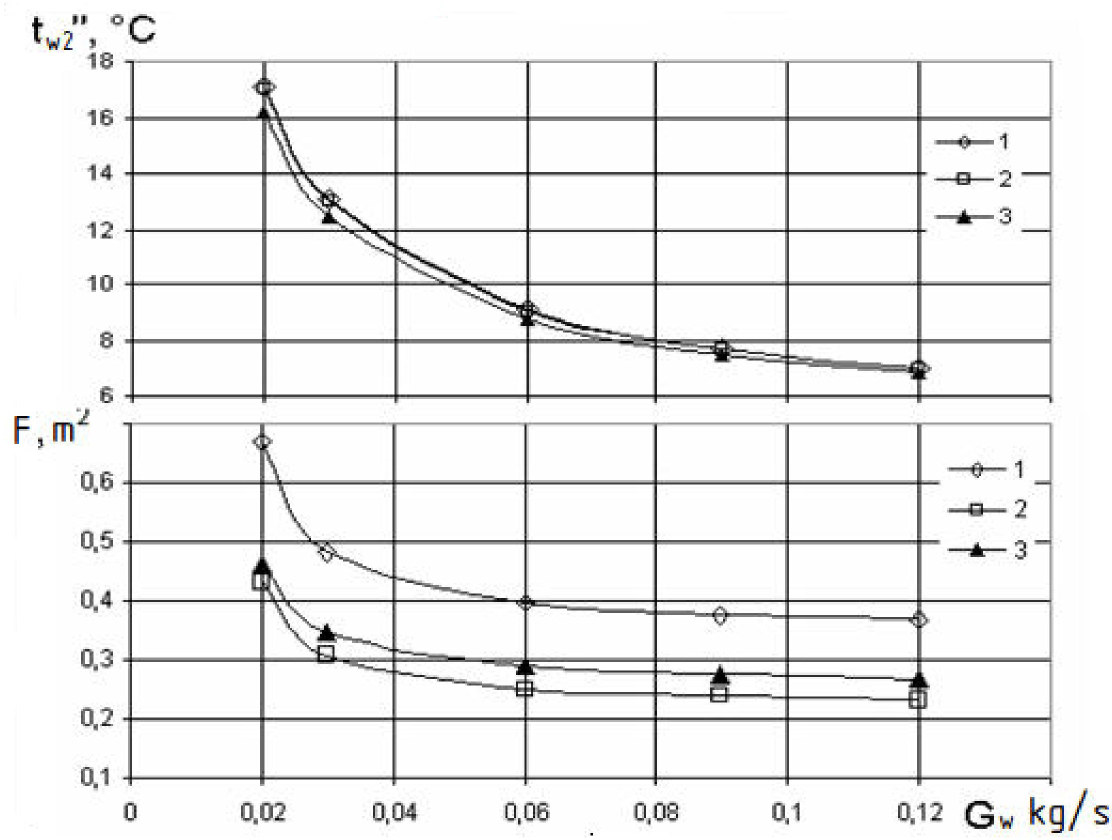

Fig. 2. Dependence of water temperature at the output of the recovery unit and coild surface area on water consumption. Heat transfer to the water from: 1 – substrates mixtures; 2 – water; 3 – chicken manure

As a result of the numerical experiment the parameters of heat exchangers operation in time for acceptable constructive parameters *d*, *L*, *F* are determined. For numerical experiment the game initial data are used as for design calculation. By the results of the numerical experiment it was revealed that the temperature of water and mixture at the output of heat recovery unit are calculated by ECM and traditional technique, coincided, this proved the reliability of ECM.

From the analysis of the results obtained the conclusion can be made that heat exchangers designed for the recovery of the heat of various mixtures provide the solution of the problem, dealing with heat recovery in BGI. The most expedient in the given case is principle diagram of heat recovery unit (Fig. 1b) for the recovery of the used mixture heat, when, taking into consideration the constructive aspects the heat exchanger surface must not be increased.

Conclusions

1. In BGU with the recovery of the fermented mixture heat and the produced biogas the output of the commercial biogas can be increased by 70…80% from the produced amount.
2. Application of ECM enabled to perform the design calculations of heat exchangers and reveal that the heat exchange areas of heat recovery units with forced convection for the recovery of heat from chicken manure and substrates mixture are 6…7 times less than the heat recovery units areas on conditions of natural convection.
3. In the heat exchanger with the cylindrical surface of heat exchange it turned out to be impossible to maintain all the constructive parameters in the conditions when it is necessary to keep to the determined volume of the mixture in heat exchanger heat recovery unit according to technological process of anaerobic treatment of the organic waste.
4. ECM enables to select, taking into consideration the technological requirements, in the water of certain temperature the necessary heat exchange surface.

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