Thermal mode of the condenser of a pyrolysis bioenergy plant with recuperation of secondary thermal energy

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Abstract. The article describes the technological scheme and the principle of operation of a pyrolysis bioenergy plant (PBEP) with a recuperative heat exchanger, which simultaneously provides hot water, gaseous and liquid biofuels to the consumer. The results of mathematical modeling of heat exchange processes in the condenser of a pyrolysis plant are presented in order to identify optimal thermal parameters for cooling the biomass pyrolysis steam. A mathematical model of the heat balance of a "mixing-displacement" type condenser (along the length of the coil) of a pyrolysis plant has been developed for calculating, selecting and thermotechnical analysis of the working cycle of the condenser, which allows to obtain the values of optimal parameters of the temperature regime. The simulation results show that the considered variants of pipes with diameters of 15 mm and 20 mm fully meet the technological requirements of condenser cooling.

1 Introduction

Under the current conditions, pyrolysis is considered worldwide as a technology for solving a complex environmental and economic problem of rational waste disposal [1].

One of the priority directions for improving the energy saving efficiency of existing pyrolysis plants are the following technological operations [2-3]:

- Increasing the use of secondary fuel and energy resources.
- Maximum use of heat recuperation.
- Solving the problem of increasing the energy efficiency of installations by optimizing the operating modes of technological installations.

To date, a number of studies and review papers on biomass (BM) pyrolysis have been published, which focus on improving the energy efficiency of pyrolysis plants using a two-stage circuit at low- and high-temperature pyrolysis sites, installations with external combustion of fuel and the use of solar energy [4-10].

A comparative analysis of the technical and energy characteristics of bioenergy plants shows that the energy intensity of BM processing in existing plants ranges from 0.3 to 1.5 MJ/kg [11]. In this regard, the development of energy-efficient bioenergy plants with the

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recuperation of secondary thermal energy in order to reduce the energy intensity of BM preprocessing is relevant.

2 Material and metods

Based on the conducted scientific research on the pyrolysis of plant BM and hydrocarbon-containing waste in order to reduce the energy intensity of the pyrolysis plant, we have proposed an experimental pyrolysis plant with a recuperative heat exchanger for pyrolysis of the processing of hydrocarbon waste to obtain alternative fuels (Figure 1).

The proposed experimental installation can provide the necessary temperature of 450-500 °C for the pyrolysis process of BM using a recuperative heat exchanger. An experimental pyrolysis plant with a recuperative heat exchanger consists of a BM preparation tank (1), a water jacket (2), a pyrolysis reactor (3), a burner device (4), a steam-gas mixture pipeline (5), a water cooler (concentrator) (6), a pyrolysis liquid tank (7), recuperative heat exchangers (8, 14), circulation pump (9), pyrogas purification unit (10), gas tank (11), control valve (12), pyrogas pipeline (13), reserve fuel (15) and circulation pumps (16, 17).

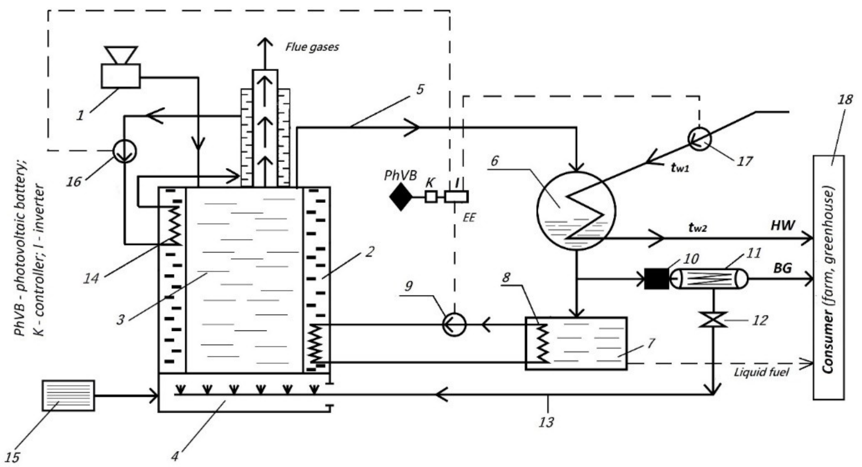

Fig. 1. Technological scheme of PBEP with recuperative heat exchanger: 1-biomass preparation tank; 2-water jacket; 3-pyrolysis reactor; 4-burner device; 5-steam-gas mixture pipeline; 6-water cooler (condenser); 7-pyrolysis liquid tank; 8-recuperative heat exchanger No. 1; 9-circulation pump; 10-pyrogas purification unit; 11-gas tank; 12-control valve; 13-pyrogas pipeline for own needs; 14-recuperative heat exchanger No. 2; 15-reserve fuel; 16, 17-circulation pumps; 18-consumer of HW, BG and TE.

The experimental PBEP works as follows. BM for preliminary preparation is loaded into the BM preparation tank 1. The prepared BM passes into the pyrolysis reactor 3. A water jacket 2 is located outside the pyrolysis reactor. At the beginning of the process, under the influence of reserve fuel 15, using a burner device 4, the pyrolysis reactor 3 is heated to a temperature sufficient to start the pyrolysis process. In the future, the biogas of the gas tank 11 is partially used to heat the pyrolysis reactor using a control valve 12 and heat recuperation of the recuperative heat exchangers 8 and 14. The temperature inside the reactor 3 rises, and pyrolysis of the loaded BM occurs, and the water jacket 2 removes heat from the heating zone of the burner device into the upper layers of BM. As a result of pyrolysis and subsequent destruction in the reactor, the vapor-gas component leaves through the pipeline of the vapor-gas mixture 5 and passes through the condenser 6. To intensify the pyrolysis process, cold water is supplied to the condenser using a circulation pump 17. During heat recuperation between the walls of cold water pipelines and the combined-cycle gas mixture, cold water is heated and supplied to the consumer. The condensed vapor-gas mixture decomposes into pyrolysis liquid and pyrogas. The pyrolysis liquid enters the pyrolysis liquid container 7, part of the pyrolysis liquid is supplied to the consumer. A recuperative heat exchanger 8 is located in the pyrolysis liquid container, in which there is water. With the help of a circulation pump 9, heat recuperation occurs between the pyrolysis liquid and the water jacket 2. The decomposed pyrogas passes through the pyrogas purification unit 10 and accumulates in the gas tank 11. Biogas is supplied to the consumer from the gas tank. A recuperative heat exchanger 14 is located in the water jacket, which makes it possible, with the help of a circulation pump 16, to utilize the heat of the outgoing flue gases into the water jacket.

The analysis of the conducted studies shows that the condenser is the main heat exchange device, which provides the energy cycle of the pyrolysis plant. To select the rational parameters of the PP condenser, in this paper, heat exchange processes are simulated in non-stationary temperature conditions.

To develop a mathematical model based on the schematic diagram of the PBEP, we present the design scheme of the "mixing-displacement" type condenser in Figure 2.

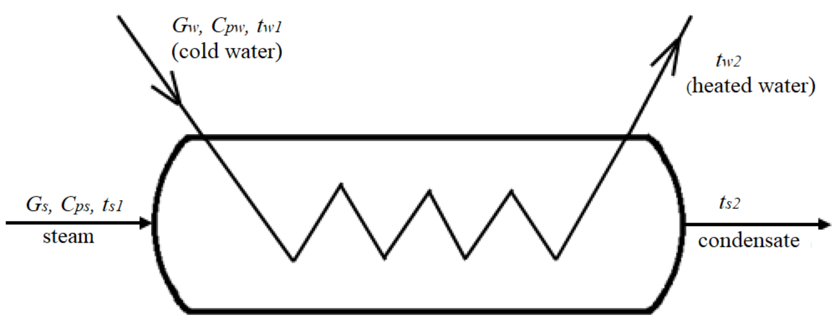

Fig. 2. Design scheme of the "mixing-displacement" type condenser.

Taking into account the stationarity of the process (the time derivative is zero), the differential equation of the thermal balance along the length of the coil [12, 13]:

$$G_w \cdot C_{pw} \frac{dt_w}{dl} = \frac{kF}{l_F}(t_s - t_{w2}) \tag{1}$$

Where, l_F – the total length of the displacement zone (coil).
Starting conditions: l=0; $t_w = t_{w1}$
Heat balance of the condenser [14-15]:

$$G_s \cdot C_{ps}(t_{s1} - t_{s2}) = \frac{kF}{l_F} \int_0^l [t_s - t_w(l)]dl \tag{2}$$

Or:

$$G_s \cdot C_{ps}(t_{s1} - t_{s2}) = G_w \cdot C_{pw}(t_{w2} - t_{w1}) \tag{3}$$

Integrate equation (1):

$$t_{w2} = t_s - (t_s - t_{w1}) \cdot e^{\left(-\frac{kF}{G_w \cdot C_{pw}} \cdot \frac{l}{l_F}\right)} \tag{4}$$

Or $\frac{kF}{G_w \cdot C_{pw}} = \text{в}$, then we get the following final equation:

$$t_{w2} = t_s - (t_s - t_{w1}) \cdot e^{-\text{в} \cdot \frac{l}{l_F}} \tag{5}$$

The main thermal engineering parameters of the PBEP condenser are given in Table 1.

Table 1. Initial data for the calculation.

No	Parameters	Designations	Units of measurement	Values
1.	Specific heat of water	C_{pw}	kJ/kg·^{0}C	4.19
2.	Cooling water consumption	G_w	kg/s	0.01÷0.05
3.	Initial water temperature	t_{w1}	^{0}C	16÷18
4.	Steam temperature	t_{s1}	^{0}C	200
5.	Heat transfer coefficient	k	W/m^2·к	200/220
6.	Full length of the zone of displacement (coil)	l_F	m	2.0
7.	Coil length	l	m	0÷2.0

Thus, the equation (5) obtained makes it possible to determine the temperature of the heated water at the outlet of the condenser. Numerical simulation results are presented in Figures 3-5.

3 Results

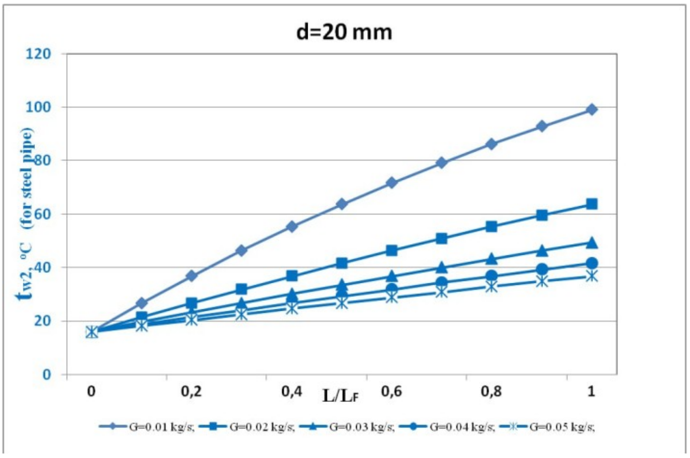

Fig.3. Graph of changes in the temperature of heated water depending on the relative length of the coil with a pipe diameter of 20 mm.

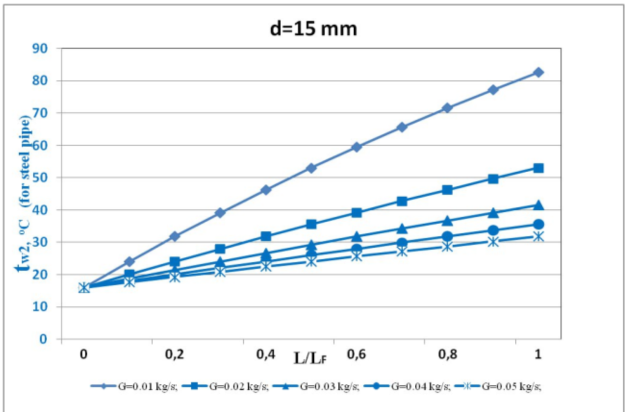

Fig.4. Graph of changes in the temperature of heated water depending on the relative length of the coil with a pipe diameter of 15 mm.

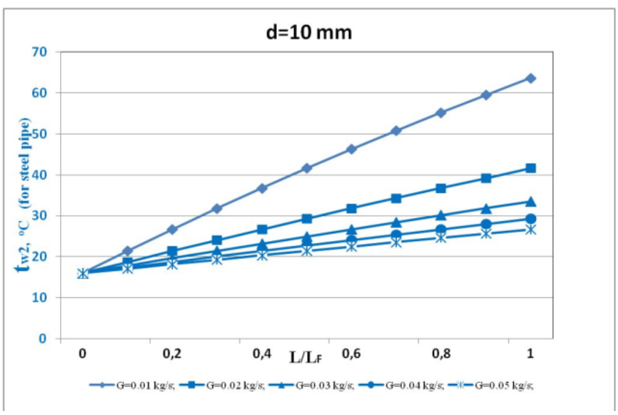

Fig.5. Graph of changes in the temperature of heated water depending on the relative length of the coil with a pipe diameter of 10 mm.

4 Discussions

The results of theoretical studies based on the method of mathematical modeling of heat exchange processes in a condenser in the cooling mode with different diameters of cooling pipes (Ø10, Ø15 and Ø20 mm) show that the cooling pipes of a condenser with a diameter d = 15 mm more efficiently provides the thermal mode of the installation.

The water temperature at the outlet of the condenser with a pipe diameter d = 15 mm ranges from 25 to 82 0 S and depends on the cooling water flow rate (Figure 4).

5 Conclusions

Based on the performed computational studies and simulation results, the following conclusions can be drawn:

- The water consumption in the condenser 0.01 kg/s and 0.02 kg / s provides an outlet temperature of 40 = 82 ^{0}C.
- The cooling water consumption of 0.01-0.02 kg/s with a pipe diameter of d = 20 mm is more acceptable for performing a cooling cycle of a vapor-gas mixture of pyrolysis.

- The condenser of the pyrolysis plant provides hot water at the outlet with a temperature not lower than 40÷82 ^{0}C with pipe diameters of 15÷20 mm with a water flow rate of 0.01÷0.02 kg/s.

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