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The use of porous metals in the design of heat exchangers to increase the intensity of heat exchange

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Abstract. Heat exchangers are widely used in heat supply systems. To increase the efficiency of heat supply systems, heat exchangers with porous metals are proposed to design. There was a test facility set up to study new types of heat exchangers. The countercurrent flow of heat carriers was activated in those heat exchangers. Freon moved through the heat exchanger pores, and water moved through the inner tubes. It should be noted that the porous materials in the heat exchangers differed in the coefficient of porosity. To be compared, one of the heat exchangers did not contain any porous material. The first test cycle proved the feasibility of using porous metals in heat exchange equipment. Afterwards, a simplified mathematical model of the heat exchanger was compiled. Such an analytical form makes a solution convenient for engineering calculations. Numerical calculations based on this model were compared with the experimental data. Heat transfer intensity of materials with different porosity was compared.

1 Introduction

Heat exchangers make one of the main elements in heat supply systems. Basically, heat supply systems use sectional counterflow water heaters or plate heat exchangers. Their heat transfer process is well-known, and it is difficult to obtain significant increase in the heat transfer coefficient. Recently, the problem of designing new heat exchangers (for example with porous metals) has become urgent [1-8].

Porous heat-conducting materials made of powdered aluminum, copper and other materials make it possible to create new efficient and compact heat exchangers [9-12].

There are special heat exchangers of the “liquid-gas” type with a phase transition of a heat carrier and without a phase transition. There are also various designs of such devices. For instance, they use a triple layer of porous metal adjacent to a heat transfer surface with a different degree of porosity. They also apply the method of transmitting a hot coolant with a phase transition through a porous metal in order to increase the heat transfer surface and its efficiency. Heat exchangers in the form of porous fins with different angles of inclination are also used. However, it should be noted that sometimes the units are expensive or it is hard to clear them out. [12-18]

Thus, nowadays heat exchangers with porous metals are being designed.

The Department of Industrial Heat Power Engineering in Tyumen Industrial University became a platform for setting up a test facility to study the effectiveness of using such materials.

The test facility is a stand where three heat exchangers with porous inserts and one heat exchanger without them are fixed. Heat exchangers are countercurrent, i.e. water flows through the central copper tubes, and freon moves through the pores of the inserts in the opposite direction. Water is pumped. The water temperature can be changed since the pump is followed by a boiler. Freon moves through a refrigeration circuit consisting of a compressor, an evaporator and a condenser. Thus, two circuits were set up in the test facility: one for water circulating, and the other for freon circulating.

The object of the research is the heat transfer process in heat exchangers of the "liquid - gas" type with a phase transition of the coolant and without a phase transition. The purpose of the work is an experimental and theoretical study of the heat transfer intensity in heat exchangers of the "water-gas" type with a phase transition of a coolant containing porous inserts of different porosity.

2 Methods

Heat exchangers are comprised of 19 copper tubes for water flow. Four cylindrical inserts of aluminum with different porosity are on them. The porosity of the inserts in the first heat exchanger is 0.4901, in the second heat exchanger the porosity of the inserts is 0.6169, in the third one the porosity of the inserts is 0.4739, in the fourth there is no porous insert. The inside of the heat exchanger with porous inserts is shown in Figure 1.

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Fig. 1. Porous aluminum inserts.

Porous inserts are cylinders of porous aluminum with a height of 50 mm and a diameter of 49 mm. There are 19 holes with a diameter of 6 mm in each of the inserts. Water moves through the tubes installed into the holes. Freon moves through the pores of the insert.

A series of experiments was carried out at the set up. The first part of the experiment was as follows: water consumption was regulated by a ball valve. The temperature changes were measured at the inlet to and from the heat exchanger. The flow rate was also recorded. The average value of a series of experiments was found. The obtained values determined the freon mass flow rate and the amount of heat Q transferred from water to freon [19].

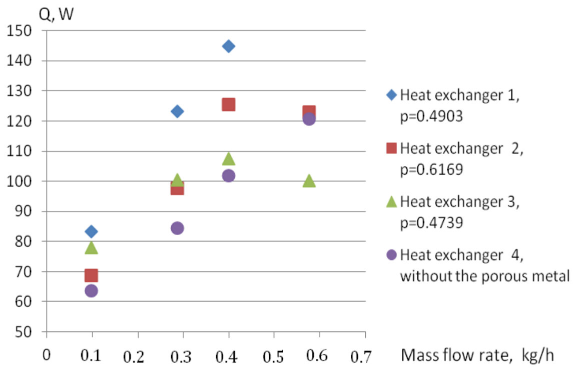

Fig. 2. Results of measurements of heat transfer intensity in heat exchangers with and without porous inserts.

The heat transfer intensity is higher for heat exchangers with porous metal inserts. Moreover, heat exchanger 4 without porous inserts has lower heat transfer intensity than other heat exchangers. The results are shown in fig.2. It can be concluded that heat exchangers with porous metals are more efficient than a conventional counterflow heat exchanger.

The next part of the experiment was carried out with an unvarying flow rate of the cooling heat carrier - water. Water of room temperature of about 20 - 22 ° C was cooled to a temperature of about 3 - 50 ° C in the circuit with freon running. The water temperature and other measurements were recorded every 2 minutes. As a result, the following data are presented in Fig. 3.

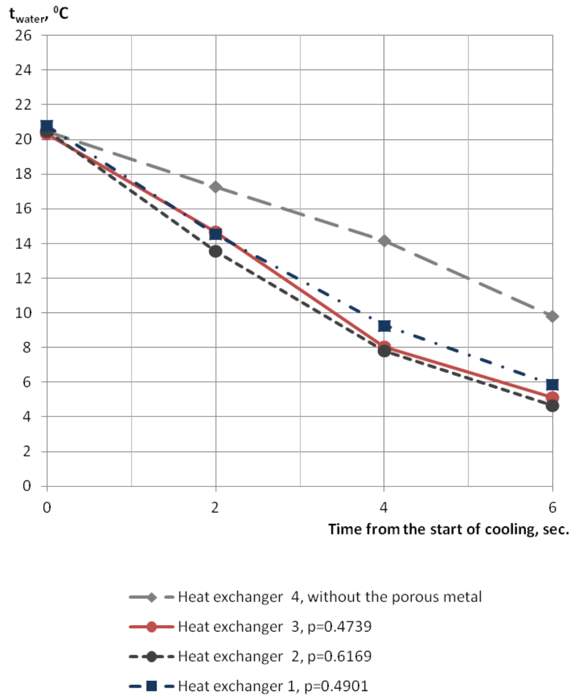

Fig. 3. The graph of temperature changes in water cooled by freon.

Summarizing the results of measurements throughout the experiment, we can register more efficient heat transfer in heat exchangers with porous aluminum. Besides, the most effective is the heat exchanger with the largest porosity among the tested heat exchangers.

Then we considered the heat transfer process inside a porous cylinder (porous insert) made of aluminum with a constant coefficient of thermal conductivity λ_c. The cylinder was well-insulated; therefore, we assumed that there was no heat exchange with the external environment. There are 19 copper tubes inside the porous cylinder. Chilled water flowes through them. An inlet temperature of water is tin (Fig. 4).

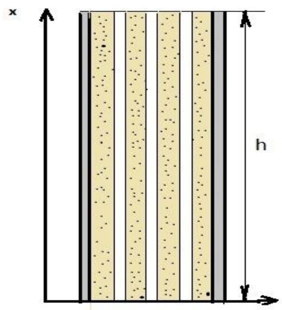

Fig. 4. Porous tube cylinder.

Freon is continuously supplied from the bottom up with a constant specific mass flow rate G_c.

Water is supplied to the tubes from top to bottom (counterflow circuit) with a constant specific mass flow rate G_B. The input water temperature was specified tin. While passing through the heat exchanger, the water is cooled and at the outlet has a temperature tout (found by calculation). The cooled water passes through the water circuit and gets into the heat exchanger with a temperature of t_{in1} = t_{out}. At the outlet of the heat exchanger the temperature will be tout1, so that the value of tin will be different in the next cycle. It is also found by calculation. Further on, the cycle is repeated manifold. So the temperature of the water circulating through the heat exchanger decreases continuously when the refrigeration circuit is operating. In order to justify such a change in temperature, it is necessary to find a dependence making it possible to determine the temperature of water at the outlet of the heat exchanger, and to compare the calculated data with the experimental ones.

The inner surface area of the tubes S is known. The volume of the porous insert V is known. The temperature of the freon at the inlet and outlet is t (0) = t_{c1} and t (h) = t_{c2}. The specific mass flow rates of freon and water (G_c and G_B) are also known. They are measured with the flow rate meter during the experiment.

Also, the specific heat of freon and water is set - c_{pc} and c_{pB}.

The porosity of the inserts p is considered as the ratio of the pore volume to the entire volume of the material. The porosity is considered uniform. Therefore, the cross section for the gas passage on a surface unit normal to the direction of the gas flow is f_w=p, and the cross section of the solid skeleton involved in heat transfer is f_c=1-f_w=1-p.

Here is the equation for the one-dimensional problem of cooling a porous body [20]:

$$\frac{d^2t}{dx^2} - \xi_c \frac{dt}{dx} = 0 \tag{1}$$

where $\frac{G_c \cdot c_{pc}}{\lambda_c (1-p)} = \xi_c$.

The temperature field becomes two-dimensional if there are tubes with water, and Eq. (1) does not work.

This equation is proposed to supplement with a function of distributed heat sources (sinks). The function describes the process of heat transfer from a porous material through the walls of copper pipes to water, with some error though.

$$q = \frac{\alpha \cdot (t_в - t) \cdot S}{\lambda_в \cdot V_в} \tag{2}$$

Consequently, the following equation succeeds:

$$\frac{d^2t}{dx^2} - \xi_c \frac{dt}{dx} + \frac{\alpha \cdot (t_в - t) \cdot S}{\lambda_в \cdot V_в} = 0 \tag{3}$$

where V_B is the volume of porous inserts, α is the coefficient of heat transfer from the copper wall to water, t_B is the water temperature at a given value of x.

Single-valuedness conditions:

$$0 \le x \le h,\ t(0) = t_{c1},\ t(h) = t_{c2} \tag{4}$$

We denote $\frac{\alpha \cdot (t_в - t) \cdot S}{\lambda_в \cdot V_в} = A$

Eq. (3) takes the form:

$$\frac{d^2t}{dx^2} - \xi_c \frac{dt}{dx} + A = 0 \tag{5}$$

Boundary value problem Eq.(3) and (4) was solved by standard methods. The function of temperature changes of the porous metal in the heat exchanger along the x axis was obtained:

$$t = t_{c1} + \frac{A}{\xi_c} x + \left(e^{\xi_c x} - 1\right) \cdot \frac{t_{c2} - t_{c1} - \frac{A}{\xi_c} h}{e^{\xi_c h} - 1} \tag{6}$$

We differentiate the obtained temperature function on variable *x*:

$$\frac{dt}{dx} = \frac{A}{\xi_c} x + \frac{\left(t_{c2} - t_{c1}\right) \cdot \xi_c - A \cdot h}{e^{\xi_c h} - 1} \cdot e^{\xi_c x} \tag{7}$$

With function Eq. (7) known, we derive the formula for the heat flow rate:

$$q = -\lambda_c \cdot (1-p) \cdot \left(\frac{A}{\xi_c} x + \frac{\left(t_{c2} - t_{c1}\right) \cdot \xi_c - A \cdot h}{e^{\xi_c h} - 1} \cdot e^{\xi_c x} \right) \tag{8}$$

The quantity ΔQ = Δq · S = (q (h) - q (0)) · S, where Q is the amount of heat. It is equal to the heat transferred from water to freon without heat loss. The volume of water in the tubes is V_T. This is the capacity of the tubes. The heat capacity and density of water are c_{pv} and ρ_v respectively. The initial water temperature is known and is equal to t_{out}. The outlet water temperature will be found at a known ΔQ by the formula:

$$t_{in} = t_{out} - \Delta t_T \tag{9}$$

where

$$\Delta t_т = \frac{\Delta Q}{c_{рв} \cdot V_т \cdot \rho_в} \tag{10}$$

3 Results and Discussion

The developed model was verified through a series of experiments evaluating its accuracy and correctness. The experiments were carried out with the following values of the main parameters: the diameter of the porous sample - d = 0.049m; the total length of the porous insert is h = 0.2 m; number of tubes - n = 19; the inner diameter of the tubes is d = 0.004 m; heat capacity of water - cf = 4187J / kg • K; thermal conductivity coefficient of aluminum - λs = 209.3 W / m · K. The same values of the main parameters were specified for theoretical calculations.

Comparative graphs below present theoretical calculations and the results of experimental measurements for each of the heat exchangers (Fig. 5-7).

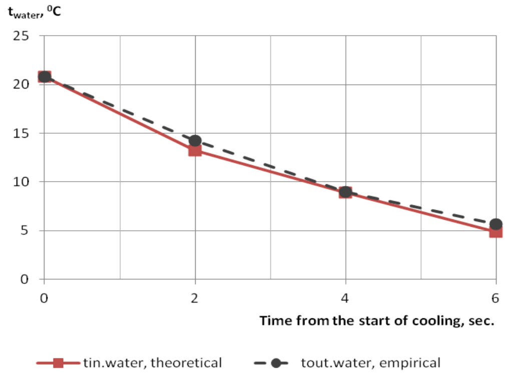

Fig. 5. Theoretical and empirical lines of temperature changes in water cooled by freon heat exchanger 1, p = 0.4901.

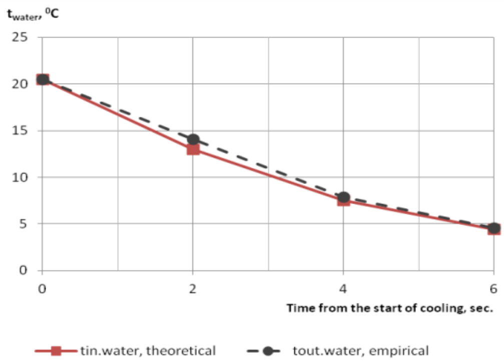

Fig. 6. Theoretical and empirical lines of temperature changes in water cooled by freon heat exchanger 2, p = 0.6169.

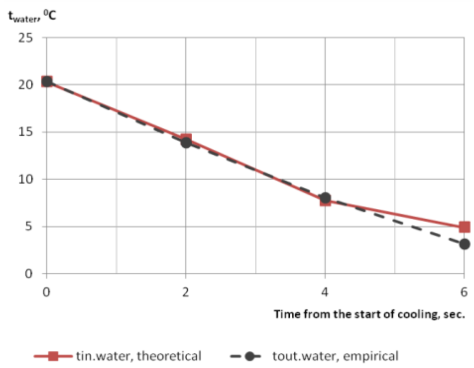

Fig. 7. Theoretical and empirical lines of temperature changes in water cooled by freon: heat exchanger 3, p = 0.4739.

The graphs show that the empirical and theoretical curves almost coincide. This verifies the model having small errors within acceptable values.

4 Conclusions

Based on the research and calculations, the following conclusions can be drawn:
1. The heat transfer rate is higher in heat exchangers with porous metal inserts compared to heat exchangers without porous metal inserts.
2. The heat transfer intensity is higher in the heat exchanger with the highest porosity p = 0.6169 compared to other tested heat exchangers with porous inserts.
3. A mathematical model has been developed to describe the heat transfer process in porous inserts of a counterflow heat exchanger.
4. A calculation equation has been derived to determine cooling degree of the hot heat carrier at the outlet of a heat exchanger, as well as determine temperature in the porous structure in any section of a heat exchanger.
5. Laboratory research proves the possibility of designing new heat exchangers with porous metals inside, they can be used in the power industry, namely in heat supply systems.

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