Abstract. This paper proposes using porous metals to boost heat exchanger efficiency. One coolant (Freon) flows through the porous metal, while the other coolant (water) flows through the narrow tubes laid inside the porous metal. The paper presents a mathematical model for a porous-metal heat exchanger, which can find metal temperature changes in any section of the heat exchanger to compare the heat transfer rate of metals of different porosity. Calculation by standard methods is not an option, as the inner surface of pores is unknown. The temperature of hot water inside the heat exchanger is to be found analytically. The obtained equations help determine the degree of cooling the first coolant (hot water). Porous heat exchangers can be used in heating systems.

1. Introduction

Increasing the heat transfer rate is one of the crucial challenges in today’s heat exchanger manufacturing. Porous metals are a promising technology for that purpose. [1-12]

Use of porous metals helps build smaller yet more efficient heat exchangers. Design types vary, but all of them have channels or intertube space filled with various porous metals in a variety of structures [13-21]

This research seeks to create a mathematical model for a porous-metal heat exchanger, which can find metal temperature changes in any section of the heat exchanger to compare the heat transfer rate of metals of different porosity. Calculation by standard methods is not an option, as the inner surface of pores is unknown.

The paper presents an experimental study of a heat exchanger based on porous aluminum. One coolant (Freon) flows through the pores, while the other coolant (cooled water) flows through the narrow tubes laid inside the porous metal.

The research team has built a test stand to experiment with such an exchanger. Results of a series of tests indicate that porous metals are indeed suitable and recommendable for use in heat exchangers. [22] The team has also obtained the equations that can find the coolant temperatures in any section of the heat exchanger. The method applies in cases when the heat transfer surface area is unknown; at the same time, it can be used to calculate the coolant heat capacity and the heat of the phase transition.

2. Experimental Results and Analysis

Mathematical model of heat transfer enabled by a low-boiling point fluid in a porous structure is complex in its general form; no precise analytical solution exists. This is why various assumptions are made to simplify calculations and transforms. When solving the problem, it is assumed that any heat
supply in a porous material is enabled by the thermal conductivity and is mediated by the gaseous phase of Freon, and that the gas and the solid do not differ significantly in temperature at any point of the porous structure. The assumption makes it far easier to solve the problem.[23]

Consider a porous aluminum cylinder with a constant heat transfer coefficient \( \lambda_c \). The temperature field inside the cylinder can be considered unidimensional; assume the same for the cooling gas, i.e. \( t=t(x) \) at \( 0 \leq x \leq h \) (a preset ultimate length) and \( t_w=t_w(x) \) at \( 0 \leq x \leq h \). To simplify the calculations, assume that the water temperature equals the mean inlet-to-outlet temperature, is constant and equals \( t_w \). The cylinder under consideration is well-insulated; thus, assume zero heat transfer to or from the environment.

Figure 1. Porous cylinder with tubes.

The porous cylinder contains 19 copper tubes carrying cooled water with a mean temperature \( t_w \), see Figure 1. The tube surface area \( S \) is known. The porous insert volume \( V \) is also known. Another known variable is the copper heat transfer coefficient \( \lambda_m \).

The temperature of Freon at the inlet and at the outlet, \( t_{c1} \) and \( t_{c2} \), is assumed to be known.

The problem also specifies the Freon and water heat capacity values, \( c_p \) and \( c_{pw} \). Specific mass flow rate of Freon and water, \( G_c \) and \( G_w \), is also known. It is therefore necessary to find the function of temperature distribution inside porous metal.

The insert porosity \( p \) is the ratio of pore volume to the total volume of the material. Porosity is deemed uniform, i.e. for each unit of a surface normal to the gas flow direction, the gas passage section \( f_a = p \), while the section of the solid skeleton \( f_s = 1 - f_a = 1 - p \). Note that if the specific mass flow rate of Freon is \( G_c \), then the mass flow rate inside a plate is \( G_c/p \).

Heat transfer in such a porous body is enabled by the thermal conductivity of the plate itself as well as by the heat transfer between the solid and the fluid flowing through the pores. Given the assumption that Freon and aluminum are equal in temperature, let us apply the methods proposed in [23] and make an equation to describe the process:

\[
\frac{d^2t}{dx^2} - \xi \frac{dt}{dx} + \frac{\alpha (t_w-t)S}{\lambda_mV_w} = 0
\]

where \( \frac{\alpha (t_w-t)S}{\lambda_mV_w} = A \) is a function of distributed heat sources (flows) that takes into account the heat transfer from aluminum to the copper tube-carried water; \( V_a \) is the volume of the copper tubes carrying water.
The constructed second-order differential equation is soluble by standard methods, which produces a function of temperature change in the porous metal of the heat exchanger:

\[ t = t_{c1} + \frac{A}{\xi_c} x + \left( e^{\xi_c x} - 1 \right) \cdot \frac{t_{c2} - t_{c1} \cdot \frac{A_h}{\xi_c e^{\xi_h}}}{e^{\xi_h} - 1} \]  

(2)

where \( \frac{A \xi_c e^{\xi_c} p_c}{\xi_c (1-p)} = \xi_c \).

Given the function (2), obtain the formula that can quantify the heat at any inner point of the porous body:

\[ q = -\lambda_c \cdot (1-p) \cdot \left( \frac{A}{\xi_c} + \frac{(t_{c2} - t_{c1}) \cdot \xi_c - A_h}{e^{\xi_h} - 1} \cdot e^{\xi_c x} \right) \]  

(3)

Experiments have generated data that can be used to estimate how far water can be cooled over a specific time while traveling from the inlet to the outlet of heat exchangers of varying porosity. Given that the laboratory stand runs in cycles, it can be used to quantify the heat water loses while flowing through the heat exchanger, and thus find the distribution of water temperature over time. Figure 2 shows the experimental results that nearly totally match the calculations by the formulas (1) to (3).

![Figure 2. Coolant temperature at the heat exchanger outlet (t°C) as a function of time (τ, s).](image)

As can be seen in the Figure, water cooling rate is the highest in a heat exchanger that has inserts of highest porosity.

3. Conclusions

The research has produced the following findings:

1. The obtained equation can be used to find the temperature of porous material and hot coolant in any section of the heat exchanger.
2. A porous-metal heat exchanger has the higher heat transfer rate, the higher the porosity.
3. The laboratory setup can now be used to make a porous heat exchanger for real-world application in heating.
4. References

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