EXPERIMENTAL STUDY ON HEAT TRANSFER AND FLOW CHARACTERISTICS OF TWO KINDS OF POROUS METAL FOAM TUBES FILLED WITH WATER

by

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The heat transfer and flow characteristics of water in a copper foam tube, a nickel foam tube, and a smooth tube are investigated in this paper. The copper foam tube and nickel foam tube are produced, and an experiment for testing the heat transfer and flow characteristics of water in metal foam tubes is set up. Experimental system validation is done in this paper, and it is found that the experimental results have a good agreement with that of published literature. The effects of two kinds of metal foam tubes and different Reynolds numbers on the heat transfer and flow characteristics of water are investigated. It is found that copper foam tube shows the best heat transfer performance, followed by the nickel foam tube, and the smooth tube has the worst heat transfer performance. It is also found that comprehensive index of heat transfer and flow increases with Reynolds number.

Key words: *heat transfer enhancement, metal foam tube, flow resistance, Reynolds number*

Introduction

Heat transfer enhancement is investigated by many researchers [1]. Heat transfer enhancement mainly includes two aspects. One method is to improve the heat conducting property of fluid in the tube, for example, nanofluids instead of water. Another method is to improve the structure of tube. Porous metal foam, as a high heat conducting property material, is widely applied in more and more fields. Many researchers have investigated the heat transfer and flow characteristics of various porous metal foams.

Some researchers used various numerical methods to study the flow and heat transfer characteristics of different metal foams. For example, aluminum metal foam [2], stainless steel metal foam [3], copper metal foam [4], aluminum and copper metal foam [5], copper and stainless steel metal foam [6].

In addition to the numerical studies on metal foam, many researchers experimentally investigated the heat transfer and flow characteristics of metal foam. Abadi *et al*. [7] and Odabaee *et al*. [8] experimentally investigated the heat transfer enhancement and pressure drop in a heat exchanger tube filled with metal foam respectively. Amani *et al*. [9] experi-

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mentally studied the convection heat transfer and flow of magnetite nanofluid in a metal foam tube. Nazari *et al*. [10] experimentally studied the convective heat transfer of nanofluid in a metal foam pipe. Mancin *et al*. [11] experimentally investigated the forced convection of air in metal foams. Dukhan *et al*. [12] experimentally investigated the thermal development of water in open-cell metal foam. De Schampheleire *et al*. [13] experimentally investigated the buoyancy-driven flow in open-cell aluminum foam heat sinks. Wang *et al*. [14] experimentally investigated the heat transfer of air in a steel foam tube. Park *et al*. [15] experimentally investigated the convective heat transfer of water in open-cell porous metal fins.

Aforementioned researchers made a great contribution to the studies on the heat transfer and flow characteristics of one kind of metal foam at high Reynolds numbers. However, the effects different kinds of metal foams on heat transfer and flow performance of fluid at low Reynolds numbers are needed to be investigated further. The main innovations of the paper are: the effects different kinds of metal foams on heat transfer and flow performances are investigated and comprehensive evaluation for thermohydraulic behavior is studied. Hence, the heat transfer and flow characteristics of water in two kinds of porous metal foam tubes at low Reynolds numbers are investigated in this paper.

Method

Experimental system

Figure 1 shows the experimental system. It mainly includes two sections which are the heat transfer test section and flow resistance test section, respectively. In addition to the two main sections, there is also a temperature control sink (DC-2030A) which is used to cool the water.

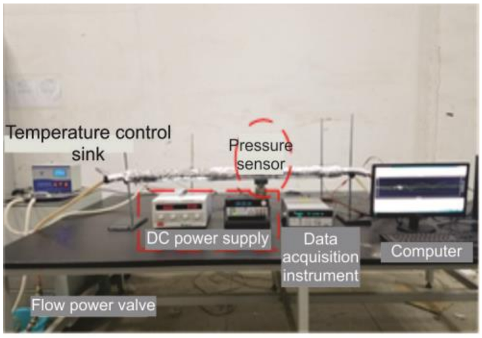


Figure 1. Experimental system

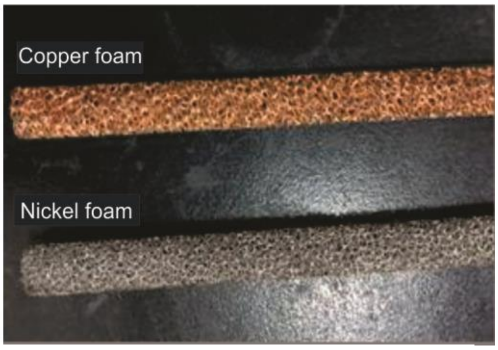
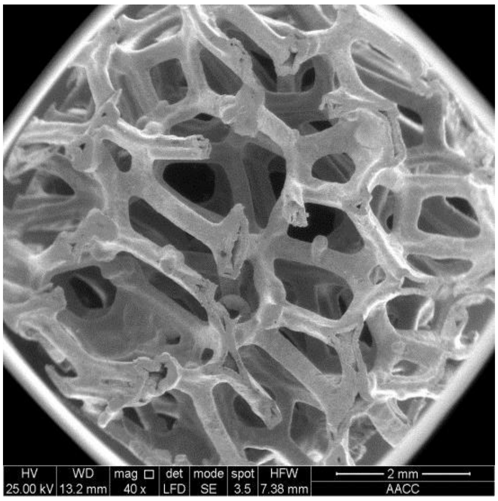
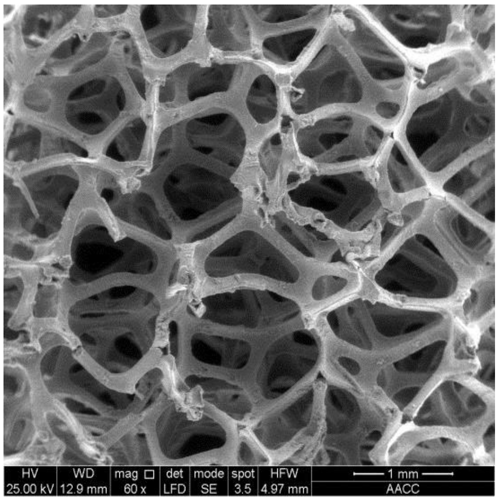


Figure 2. Copper and nickel foam

The copper smooth tubes in the heat transfer test section and flow resistance test section are all filled with copper foam and nickel foam, respectively. The length of the metal foam tube is 1200 mm, the outside diameter of the tube is 10 mm, and the inside diameter of the tube is 9 mm. The middle section 1000 mm of the tube is used in the experiment and 100 mm section is left in the two ends of the tube, respectively, in order to avoid the entrance effect. The copper and nickel foam are presented in fig. 2. The porosities of copper foam and nickel foam are all 98%, and the pore densities of copper foam and nickel foam are all 40 PPI. The SEM images of copper and nickel foam are shown in fig. 3. It can be found that metal foams are porous, which is advantageous for heat transfer enhancement. Thermal conductivities of cooper and nickel are shown in tab. 1.



(a)



(b)

Figure 3. The SEM images of copper and nickel foam; (a) copper, (b) nickel

Table 1. Thermal condutivities of copper and nickel

Material	Thermal conductivity, [W/mK]
Copper [16]	400
Nickel [17]	90.3

Figure 4 shows the schematic diagram of experimental system. For the heat transfer test section, the metal foam tube is heated by a resistance wire connected to a DC power. The temperatures of outside of the tube are measured by ten T-type thermocouples uniformly distributing in outside of the test tube, and the other ends of thermocouples are connected to a data acquisition instrument (Agilent 34972A). The temperatures of inlet and outlet of water in the tube are measured by two K-type thermocouples. Insulating layer is used outside of the test tube to prevent the heat losing. The insulating layer materials are aluminum silicate insulation asbestos with 30 mm in thickness and rubber pipe-sleeve with 10 mm in thickness.

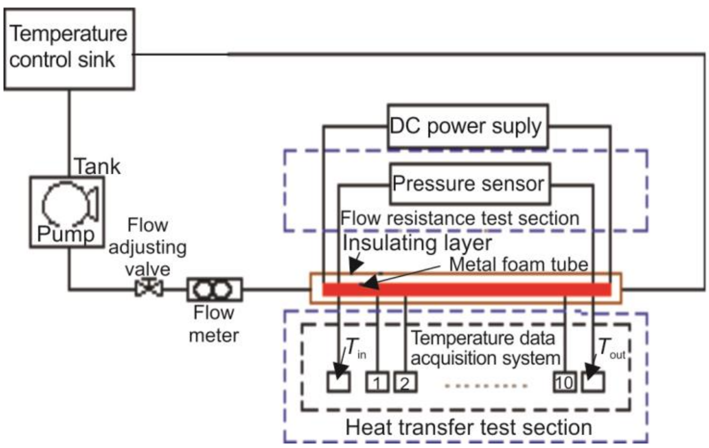


Figure 4. Schematic diagram of experimental system

For the flow resistance test section, a same metal foam tube with the tube in the heat transfer test section is used in this experiment. The pressure drop is measured by a differential pressure instrument.

Data processing

The heat absorbed by fluid Q_f is calculated:

$$Q_f = c_p q_m \left(T_{out} - T_{in}\right) \tag{1}$$

where c_p is the specific heat of fluid, q_m – the mass-flow rate, and T_{out} and T_{in} are outlet and inlet temperature of fluid, respectively.

The average temperature of fluid, T_f, in the tube is calculated:

$$T_f = \frac{T_{out} + T_{in}}{2} \tag{2}$$

The average temperature of outer wall of tube T_{ow} is shown:

$$T_{ow} = \frac{\sum_{i=1}^{10} T_w(i)}{10} \tag{3}$$

where $T_w(i)$ is the temperature of thermocouples attached in the outer wall of tube, and there are ten thermocouples attached uniformly in the outer wall of tube.

The average temperature of internal wall of tube, T_{iw}, can be calculated:

$$T_{iw} = T_{ow} - \frac{Q_f \ln\left(\dfrac{r_o}{r_i}\right)}{2\pi\lambda l}, \quad (i = 1, 2, 3...10) \tag{4}$$

where r_o and r_i are the external radius and internal radius of tube, λ – the thermal conductivity of tube, and l – the length of tube.

The convective heat transfer coefficient, h_f, is calculated:

$$h_f = \frac{Q_f}{\pi d_e l \left(T_{iw} - T_f\right)} \tag{5}$$

where d_e is the equivalent diameter of tube for smooth tube and d_e is the equivalent diameter of pore of metal foam for metal foam tube.

Nusselt number is calculated:

$$\text{Nu} = \frac{h_f d_e}{\lambda_f} \tag{6}$$

where λ_f is the thermal conductivity of fluid in the tube.

Reynolds number is shown:

$$\text{Re} = \frac{\rho u d_e}{\mu_f} \tag{7}$$

where ρ is the density of fluid, u – the velocity of fluid, and μ_f – the dynamic viscosity of fluid. The critical Reynolds number of the smooth tube between laminar flow and turbulent flow is 2300, however, the critical Reynolds number of metal foam tube is about 10 [18].

Frictional resistance coefficient of fluid, f, is presented:

$$f = \frac{2d_e}{\rho u^2}\frac{\Delta p}{\Delta l} \tag{8}$$

where $\Delta p/\Delta l$ is the pressure drop per unit length.

The equation of comprehensive evaluation between heat transfer and flow resistance, ς, is shown [19]:

$$\varsigma = \frac{\text{Nu}_f}{\text{Nu}_s} \bigg/ \left(\frac{f_f}{f_s}\right)^{\frac{1}{3}} \tag{9}$$

where the subscripts, f, represents the metal foam tube, and s represents the smooth tube.

Uncertainty analysis

Experimental error is caused by the accuracy of equipment in the experimental system. The corresponding error equations are shown [20]:

$$\frac{\delta \text{Nu}}{\text{Nu}} = \sqrt{\left(\frac{\delta Q_f}{Q_f}\right)^2 + \left(\frac{\delta T}{T}\right)^2} \tag{10}$$

$$\frac{\delta f}{f} = \sqrt{\left(\frac{\delta p}{p}\right)^2 + \left(\frac{\delta l}{l}\right)^2 + \left(\frac{\delta q_m}{q_m}\right)^2} \tag{11}$$

where the accuracy of DC power is ±5.0%, the accuracy of thermocouple is ±0.1%, the error of Nusselt number can be obtained from eq. (10) and is about ±5.0%. The accuracy of pressure transducer is ±0.5%, the accuracy of length is ±0.1%, the mass-flow rate of mass-flow rate is ±1.06%, and the error of frictional resistance coefficient can be obtained from eq. (11) and is about ±1.29%.

Results and discussion

Experimental system validation

Before the experiment of water in metal foam tube, in order to verify the reliability and accuracy of the experimental system, the results of heat transfer and flow characteristics of water in a smooth tube are compared with that of published literatures. Figure 5 gives the comparisons of Nusselt numbers and frictional resistance coefficients between the experimental results and the results of literatures in a smooth tube. It can be found from fig. 5 that the maximum errors of Nusselt number and ln(100*f*) are 3.5% and 2.1%, respectively. This proves that the experimental results show a good agreement with that of published literatures [21, 22], which verifies the reliability and accuracy of the experimental system.

Experimental results and discussions

The heat transfer characteristics of water in a nickel foam tube, a copper foam tube and a smooth tube at different Reynolds numbers are investigated, respectively. Figure 6 shows the changes of Nusselt numbers with Reynolds numbers. Figure 7 presents the Nusselt numbers ratios between the metal foam tubes and the smooth tube.

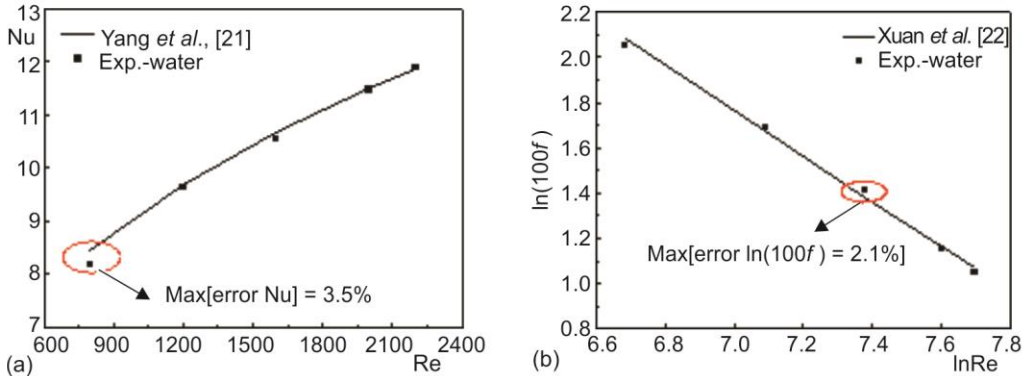


Figure 5. Comparisons of Nusselt numbers and frictional resistance coefficients between the experimental results and the results of literatures in a smooth tube; (a) Nusselt numbers (b) frictional resistance coefficients

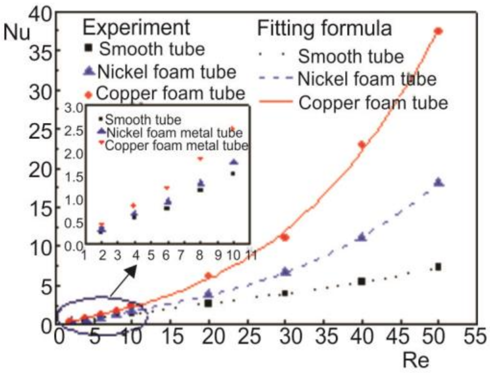


Figure 6. Changes of Nusselt numbers with Reynolds numbers

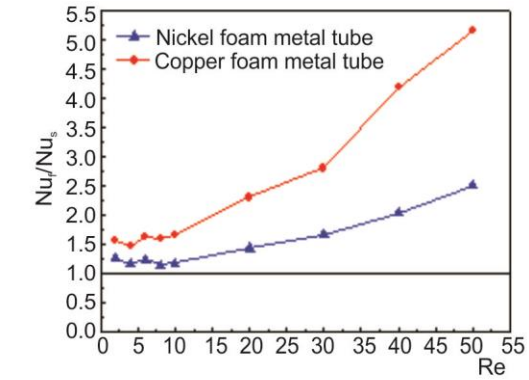


Figure 7. Nusselt number ratios between metal foam tube and smooth tube

It can be seen from fig. 6 that Nusselt numbers increase with Reynolds numbers. The increasing Reynolds numbers enhance the turbulivity of fluid, reduce the thickness of laminar boundary-layer and improve the heat transfer performance. It can be also found that the water in copper foam tube shows the best heat transfer performance, followed by the nickel foam tube, and the smooth tube has the worst heat transfer performance. The metal foam is a porous structure channel which has a high thermal conductivity itself, and the holes in the metal foam are interconnected. The interconnected holes can disturb and reduce the thickness of laminar boundary-layer and improve the heat transfer performance. Therefore, the metal foam tube shows a better heat transfer performance than smooth tube, which is because that the thermal conductivity of copper foam is much higher than that of nickel foam. Hence, the water in copper foam tube shows the better heat transfer performance than water in nickel foam tube. Fitting formula between Nusselt number and Reynolds number is shown in eq. (12) based on the data of fig. 6, and the constants in eq. (12) are given in tab. 2:

$$\mathrm{Nu} = \mathrm{A} + \mathrm{BRe} + \mathrm{CRe}^2 + \mathrm{DRe}^3 \tag{12}$$

Table 2. Constants in eq. (12)

Kind of tube	A	B	C	D
Smooth tube	–0.096	0.16555	–0.0019	3.0837E-5
Nickel tube	–0.16094	0.20728	–0.00316	1.2708E-4
Copper tube	0.04588	0.19608	3.05139E-4	2.1639E-4

It can be found from fig. 7 that water in copper foam tube and nickel foam tube can enhance the heat transfer by 413.8% and 149.6% at best compared with water in smooth tube, respectively. The metal foam tubes show an excellent heat transfer performance, especially the copper foam tube. It can be also seen that there is a small enhancement for metal foam tube when Re = 2～10 compared that when Re ≥ 10. The highest enhancement for copper foam tube and nickel foam tube are 64.9% and 25.0% when Re = 2～10, respectively. The critical Reynolds numbers between laminar flow and turbulent flow for metal foam tubes and smooth tube are different. The critical Reynolds number of the smooth tube between laminar flow and turbulent flow is 2300, however, the critical Reynolds number of the metal foam tube is about 10. It is laminar flow for metal foam when Re = 2～10 while it is turbulent flow when Re ≥ 10. The disturbance in channel of metal foam is small at laminar flow but big at turbulent flow. Hence, there are a small enhancement at low Reynolds number and a big enhancement at high Reynolds number.

In addition to the study on heat transfer, the flow characteristics of water in metal foam tubes and smooth tube are also investigated. Figure 8 shows the changes of pressure drop with Reynolds numbers. Figure 9 presents the changes of frictional resistance coefficients with Reynolds numbers. It can be found from figs. 8 and 9 that pressure drop and frictional resistance coefficient of metal foam tubes are bigger than that of smooth tube. It can be also found

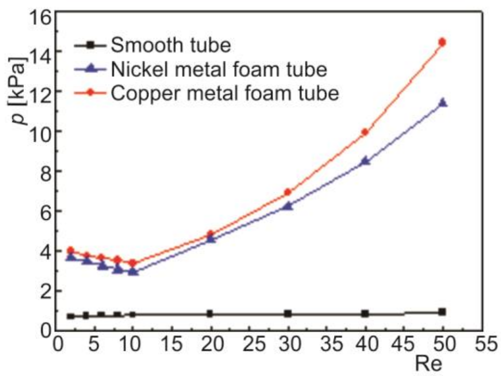


Figure 8. Changes of pressure drop with Reynolds numbers

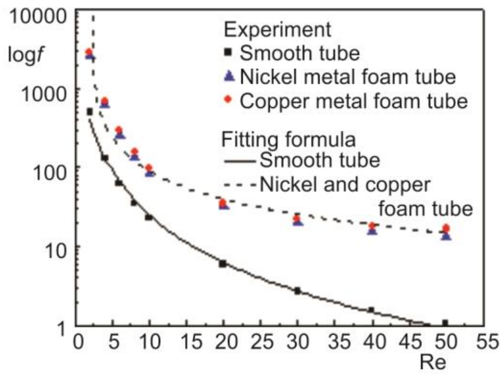


Figure 9. Changes of frictional resistance coefficients with Reynolds numbers

that there are small differences in pressure drop and frictional resistance coefficients between copper foam tube and nickel foam, which is due to the same pore densities and structures of copper foam and nickel foam. Fitting formula between frictional resistance coefficient and Reynolds number is shown in eq. (13) based on the data of fig. 9, and the constants in eq. (13) are given in tab. 3:

$$\log f = \frac{1}{A + B\text{Re}} \tag{13}$$

Metal foam enhances the heat transfer performance but it also increases the flow resistance of water. In order to comprehensively analyze the heat transfer and flow characteristics of water in metal foam tubes, the fig. 10 is given based on the eq. (9). It can be found from fig. 10 that comprehensive index, ς, increases with Reynolds number. For the Reynolds number range ($2 \le Re \le 50$) of this experiment, metal foam is advantageous to heat transfer and flow of water, and the biggest comprehensive index ς appears at Re = 50.

Table 3. Constants in eq. (13)

Kind of tube	A	B
Smooth tube	4319.09586	–2.14975
Nickel + copper foam tube	0.0028	0.0014

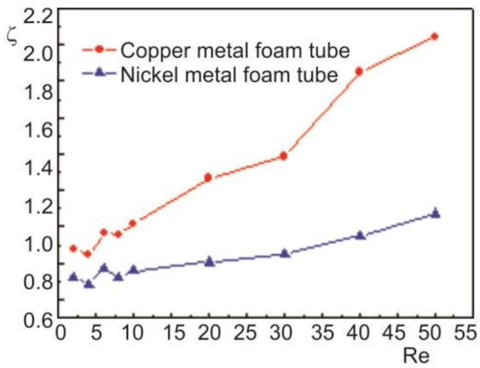


Figure 10. Comprehensive analysis of water in copper and nickel foam tube

Conclusions

The heat transfer and flow characteristics of water in a copper foam tube, a nickel foam tube and a smooth tube are investigated in this paper. Some conclusions are obtained as follows.

- Copper foam tube shows the best heat transfer performance, followed by nickel foam tube, and the smooth tube has the worst heat transfer performance.
- The highest enhancement for water in the copper foam tube and nickel foam tube are 64.9% and 25.0% compared with water in the smooth tube when Re = 2～10 (laminar flow for metal foam), respectively.
- Water in the copper foam tube and nickel foam tube can enhance the heat transfer by 413.8% and 149.6% at best compared with water in the smooth tube when $Re \ge 10$ (turbulent flow for metal foam), respectively.
- Pressure drop and frictional resistance coefficient of metal foam tubes are bigger than that of the smooth tube. It can be also found that there are small differences in pressure drop and frictional resistance coefficients between copper foam tube and nickel foam tube.
- Comprehensive index, ς, increases with Reynolds number. For the Reynolds number range ($2 \le Re \le 50$) of this experiment, metal foam is advantageous to heat transfer and flow of water, and the biggest comprehensive index ς appears at Re = 50.

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