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Enhancing boiling and condensation co-existing heat transfer in a small and closed space by copper foam inserts

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ABSTRACT

This paper aims at enhancing the boiling-condensation co-existing phase change heat transfer process inside a small and closed space by inserting copper foams into the space. The working fluid is deionized water. The pore density of copper foam used is 20 PPI and the porosity is 0.96. The inserts used include cut and non-cut copper foam blocks. Experiments were carried out to study the influences of working fluid filling ratio, cut and non-cut copper foam blocks on boiling and condensation co-existing heat transfer inside a small and closed space that is 60 mm in diameter and 33 mm in height. Experimental results show that, although there is an optimum filling ratio for boiling heat transfer coefficient obtaining its largest value, there is no such optimum ratio for condensation if the space is filled with non-cut copper foam block. However, if the space is filled with the cut copper foam block, then there is an optimum filling ratio at which both boiling and condensation heat transfer coefficient acquire their maximum value. Compared with that without copper foam inserts, although inserting non-cut copper foam block into the space can enhance boiling heat transfer, it weakens condensation and the overall heat transfer process; and inserting the cut copper foam block can enhance both boiling and condensation heat transfer and therefore is a good practice for enhancing the boiling-condensation co-existing phase change heat transfer process inside small and closed spaces.

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1. Introduction

Nowadays, computer CPUs are becoming more and more integrated with the rapid development of micro electronic technology. The CPUs generate more and more heat because of reduced size, increased speed and power consumption. And this is why people are paying greater attention to high heat-flux electronic component cooling.

Flat heat pipe has a good performance in leveling radial temperature distribution with limited increase in axial heat transfer thermal resistance. This is achieved through the boiling and condensation co-existing phase change heat transfer of working fluid. Therefore, one can understand that the boiling and condensation co-existing phase change heat transfer process in this small and closed space [1,2] in flat heat pipes is of essential importance. Liou et al. [3] made a visualization study of flat heat pipe welded with screen and measured the heat transfer resistance of boiling surface. Their experimental results show that the minimum heat transfer resistance is achieved when the liquid film is thinnest. Do et al. [4] developed a mathematic model for predicting the thermal performance of a flat micro heat pipe with a rectangular grooved wick structure. Using this model, the maximum heat flux of the flat micro heat pipe with a grooved wick structure was obtained by optimizing the geometry groove parameters. Hassan et al. [5] performed a numerical study of flat heat pipes having the wick of sintered metal powder with a three-dimensional model. Their results confirmed that there did exist a good motion of working fluid in the wick and vapor regions. Xu et al. [6] found that the composite porous surface enhanced the heat transfer by increasing active nucleation sites and the bubble departure frequency. Kumaresan et al. [7] conducted an experimental study on the performance of sintered wick and wire-screen wick heat pipes, and found that the thermal resistance of the sintered wick heat pipe is 13.92% smaller than that of the wire-screen wick heat pipe. Lefèvre et al. [8] compared the wire-screen heat pipe and the groove heat pipe. Their results showed that the heat transfer performance of the groove heat pipe was much better.

As a new-style porous material, copper foam has high porosity, large surface area and great permeability [9,10]. Therefore, inserting copper foam into the small and closed space of flat plate heat pipes might enhance heat transfer by increasing the number of active nucleation and the contact area between working fluid and the boiling surface. Xu et al. [11] conducted a visualization

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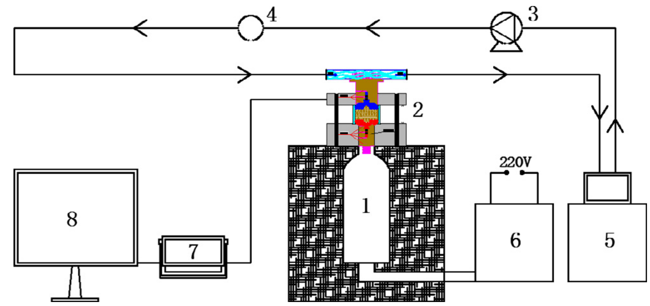
and heat transfer performance study of pool boiling of acetone at atmospheric pressure in copper foam. They found that copper foam has a strong effect on pool boiling. Yang et al. [12] welded a layer of copper foam on a flat copper surface and investigated its influences on pool boiling. Compared with the plain smooth copper surface, copper foam did increase the number of active nucleation and the contact area between working fluid and boiling surface, but at the same time, it also increased the resistance for bubbles releasing. Xu et al. [13] carried out an experimental study of pool boiling heat transfer in gradient metal foams at atmospheric pressure. Their results showed that the boiling surface welded with gradient metal foams has a bigger heat transfer coefficient than the surface welded with normal metal foams. And they argued this is because the PPI of under-layer of the metal foam is bigger than that of the upper-layer, the under-layer metal foam increases the number of active nucleation and the upper-layer metal foam decreases the resistance of bubbles releasing compared with that of no-gradient metal form. Zhou et al. [14] explored the influences of filling copper and nickel foam on the performance of loop heat pipes and their filling amount was set at 20 ml, 40 ml and 60 ml, respectively. The start time and the thermal resistance of the metal foam filling volume of 40 ml were shorter and smaller than that of 20 ml and 60 ml. Qu et al. [15] investigated pool boiling for the case that the heating surface was covered with open V-grooves of the copper foam. Their results showed that open V-grooves strengthened boiling heat transfer. Rybár et al. [16] carried out a comparative experimental thermal performance study of standard design heat pipe evacuated tube collector and collector with parallel flow manifold header with metal foam structural element and concluded that the solar collector with manifold header based on metal foam showing a performance increase around 25%. Mancin et al. [17] presented an experimental investigation of the solid-liquid phase change process of three natural paraffin waxes, the experimental results clearly showed that the presence of the metal foam matrix improved the heat transfer capabilities of the passive system allowing for lower surface temperature compared to no-metal-foam case, at the same imposed heat flux. Ji et al. [18] investigated film condensing of refrigerant R134a on single horizontal tube coated with open cell copper foam and found the enhanced ratio of all the coated tubes compared with that of the plain tube ranges from 2 to 3. Xu et al. [19] numerically investigated forced convective heat transfer of fluid (with nanoparticles) in metal-foam duct and the velocity and temperature fields were obtained. And the results showed that heat transfer enhancement with nanofluid could not offset pressure drop increase.

Although there are as many reports on enhancing boiling, condensation and even single phase heat transfer by metal foam as one can expect, metal forms have not been used for enhancing boiling and condensation co-existing phase change heat transfer in small and closed spaces as far as the present authors could know. In this paper, we try to enhance the boiling-condensation co-existing heat transfer inside a small and closed space by inserting copper foam. The experimental phenomena are recorded by a high-speed camera, the mechanisms that copper foam enhances the boiling and condensation co-existing phase change heat transfer are explored and the experimental phenomena are analyzed.

2. Experimental apparatus and procedure

2.1. Experimental system

Experimental system is shown in Fig. 1 which is almost the same as that presented in our previous work [20]. It includes a heating unit, a test section, a pump, a flow meter, a low-temperature thermostat bath, a DC power supply, a data acquisition and a personal computer. The experimental procedures and methods are also basically same as described in [1]. The only difference is that cut and non-cut copper foam blocks are inserted into the phase change chamber in the experiments presented in this paper.



1: heating unit 2: test section 3: pump 4: flow meter
5: low-temperature thermostat bath 6: DC power
7: data acquisition(Agilent34970A) 8: computer

Fig. 1. Experimental system diagram.

The heating unit and the test section are shown as Fig. 2. The heating unit is a brass rod of a diameter of 60 mm with 4 electric heaters of a working voltage of 250 V and a power of 400 W inserted. The head of heating unit connects with the test section which includes the heating copper rod, the phase change chamber and the cooling copper rod. The heating copper rod and cooling copper rod are all inserted into Teflon blocks with interference fit, as shown in Fig. 2. And the diameter of the heating and cooling copper rod is 40 mm. The heating power of the heating copper rod is regulated and controlled by adjusting the voltage of the DC power supply. A highly transparent quartz glass tube (60 mm in inner diameter, 5 mm in wall thickness and 33 mm in height) is used as the side wall of the phase change chamber and the height of the confined chamber (the small and closed space). The 12 °C cooling water flows through the cooling copper rod of the test section. the flow rate of the cooling water is 1.974×10^{-4} m^3/s and its design flow velocity is 2.52 m/s. T-type thermocouples with shields (the shield diameter is 1 mm) are embedded in copper rod and are fixed by the corresponding thermocouple holes (2 mm in diameter) in the Teflon blocks. When the heat flux of the heating copper rod is equal to the heat flux of the cooling copper rod, the system reaches steady-state. The data acquisition and computer collect the data of temperature and pressure and the high speed camera reports the boiling and condensation phenomena. The experimental data measurement instruments are exactly same as that reported in [1] and omitted here.

2.2. Copper foam

The copper foam used was bought from Shanghai Zhongwei New Material Co. Ltd with a pore density of 20 PPI and a porosity of 0.96. The copper foam block is cut into a cylinder that is 60 mm in diameter and 33 mm in height as shown in Fig. 3a and then inserted into the test section to fill the whole space. We call this copper foam block used in our tests as the non-cut one. Due to the reason which will be introduced later on, a cut copper foam block is also used as the test section insert. The cut copper foam block is actually the one that is obtained by cut away the central part of 40 mm in width and 27 mm in height from the non-cut one and then the top part of the cut copper foam is an annulus whose thickness is 3 mm, outer diameter 60 mm and inner diameter 40 mm as shown in Fig. 3b. The bottom layer thickness of the cut copper foam block is also 3 mm.

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