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Enhancing boiling and condensation co-existing heat transfer in a small and closed space by heat-conduction bridges

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ABSTRACT

This paper aims at enhancing the boiling and condensation co-existing phase change heat transfer process inside a small and closed space by heat-conduction bridges. The working fluid is deionized water and the copper heat-conduction bridges are machined directly on the boiling surface and connect the boiling and the condensation surface. Three different heat-conduction bridges that are all rectangular pillars of different sizes and layouts are tested. Experiments were carried out to study the influences of working fluid filling ratio, the cross sectional area size of the heat-conduction bridge and the gap between the heat-conduction bridges (the bridge gap) on boiling and condensation co-existing heat transfer inside the small and closed space. Experimental results show that the heat-conduction bridges can greatly enhance the boiling and condensation co-existing heat transfer process. The optimum filling ratio is 50% for 3 type heat-conduction bridges. The boiling, condensation and overall heat transfer coefficient of the heat-conduction bridges whose cross-sectional area is 2 mm × 2 mm and bridge gap is 1 mm (HCB-C) is the largest among the three heat-conduction bridges.

1. Introduction

Nowadays electronic elements are highly integrated as modern microelectronic technology is progressing at a surprisingly rapid speed. The electronic elements, especially central processing units (CPUs) generate larger and larger heat flux because of reduced size, increased speed and power consumption. And this makes people pay greater attention to high heat-flux electronic component cooling technologies.

Flat plate heat pipe has a good performance in leveling radial temperature distribution with limited increase in axial heat transfer thermal resistance. This is achieved through 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 plate 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 the thinnest. Do et al. [4] developed a mathematic model for predicting the thermal performance of a flat plate 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 plate 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. Wang et al. [6] designed two types of flat plate heat pipe, one is deep-micro-channeled and the other one is staggered-channeled. The measured thermal resistance was 0.183 W/K and 0.071 W/K, respectively. Liu et al. [7] designed a copper sintered heat pipe and tested its startup and heat transfer performance. Their experimental results showed that the start-up power and start time of loop heat pipe significantly reduced. Xu et al. [8] compared the smooth surface and the dendritic structure surface, and found that the dendritic structure surface enhanced the heat transfer and increased the number of active nucleation sites and the frequency of bubble departure. Chen et al. [9] used the sintered technology and processed the porous structure on the evaporation of heat pipe, and the porosity of the porous structure is 69% and 65%, respectively. The results showed that the heat transfer effect of 69% is better than that of 65%. Kumaresan et al. [10] conducted an experimental study on the performance of sintered wick and wire-screen wick heat pipes, and found that

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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. [11] compared the wire-screened and the grooved heat pipe. Their results showed that the heat transfer performance of the grooved heat pipe was much better. Zhang et al. [2] made the ribbed treatment on boiling surface of the boiling-condensation co-existing phase change chamber, and found that the ribbed treatment increased the number of bubble and enhanced the boiling heat transfer. Hong et al. [12] compared different size of copper particle sintered porous wick, and the optimum diameter of copper particle and the optimum coating thickness were given. Schampheleire et al. [13] proposed a fiber capillary wick for heat pipes and found that the heat transfer performance of the fiber capillary wick is the best, compared with mesh capillary wick and powder sintered capillary wick. Sven et al. [14] developed a three-dimensional numerical model for flat plate heat pipes which accounts for the effect of wick structure in determining the evaporation rate at the liquid–vapor interface. Wong et al. [15] studied the evaporation characteristics in a groove-wicked flat plate heat pipe charged with water and found that the evaporator resistance first remained at a low value before local dryout appearing beyond a certain heat load and then increased in a growing pace in response to the expanding dryout zone. Koito et al. [16] carried out the numerical simulation of the flat heat pipe with wire mesh structure, and gave the temperature field, pressure field and velocity field inside the heat pipe. Ji et al. [17] manufactured a novel integrated flat heat pipe (IFHP) that a layer of compressed copper foam was sintered on the inner surface of the evaporator bottom plate. The results indicate that the IFHP with copper foam as a porous network wick presents excellent heat performance. Lv et al. [18] designed the novel wick structure made of super-hydrophilic sintered copper mesh screen was employed to provide strong capillary force as well as low flow resistance for working fluid. It is found that the ultra-thin flat heat pipe (UTFHP) had much lower evaporator temperature and much smaller thermal resistance compared with copper sheet. Ling et al. [19] used the porous copper fiber sintered sheets (PCFSS) as wick which is inserted into the loop heat pipes (LHP). Experimental results demonstrated that LHP with rough PCFSS exhibited lower thermal resistance.

As better as the temperature-leveling performance could be of flat plate heat pipe, the axial heat conduction is actually degenerated compared with a pure copper plate if only the plate is not extremely thick due to the fact that the boiling and condensation inside the flat plate heat pipe actually increases the axial thermal resistance [20]. To be more explicitly, the axial thermal resistance of the flat heat pipe is greater than that of a copper plate that is of the same thickness as the flat plate heat pipe. Based on this understanding, it is proposed in this paper that a number of heat conduction bridges are fabricated on the boiling surface that extend to the condensation surface to enhance the heat transfer in small and closed spaces and flat plate heat pipes. The heat conduction bridges, as the name indicates, provide an additional pathway for heat transfer from the boiling surface to the condensation surface, and at the same time, might provide more nucleation sites for both boiling and condensation and thus phase change heat transfer may be enhanced. It should be stressed, although the heat conduction bridges proposed in this paper are something similar to pin fins, however, their functions are quite different. The pin fins that were reported in the literature are mainly for enhancing boiling heat transfer only, say for example, the references [21,22]. The experimental phenomena are recorded by a high-speed camera, the mechanisms that the heat-conduction bridges enhance the boiling and condensation co-existing phase change heat transfer are explored and the experimental phenomena are analyzed. And the differences of enhancing heat transfer for the different cross sectional area size of the heat-conduction bridge and the different gap between the heat-conduction bridges are also explored.

2. Experimental apparatus and procedure

2.1. Experimental system

Experimental system is shown in Fig. 1 which is almost the same as that was described in our previous work [23]. 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 the phase change chamber is filled with the heat-conduction bridges instead of copper foam.

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 $1.974 \times 10^{-4}\ m^3/s$ 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 records the boiling and condensation phenomena. The experimental data measurement instruments are exactly same as that reported in [1] and omitted here.

2.2. Heat-conduction bridges

The heat-conduction bridges are actually the fins that are fabricated directly on the boiling surface and of a height of 33 mm ensuring that they will keep certain contact to the condensation surface, as shown in Fig. 3. Three different test surfaces of different heat-conduction bridge sizes were manufactured and were labeled as HCB-A, HCB-B and HCB-C as shown in Fig. 3. All heat-conduction bridges in these three test surfaces are of a square cross section of different lateral sizes and a height of 33 mm. The cross section size of each heat-conduction bridge of HCB-A is 2 mm × 2 mm and the gap between every two heat-conduction bridges is 2 mm. HCB-A has 80 pillars and these pillars form 18 grooves and 69 crossing points on the boiling surface. The cross section size of each heat-conduction bridge of HCB-B is 3 mm × 3 mm and the gap between every two heat-conduction bridges is 1mm. HCB-B has 80 pillars and these pillars form 18 grooves and 69 crossing points on the boiling surface. The cross section size of each heat-conduction bridge of HCB-C is 2 mm × 2 mm and the gap between every two