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Experimental investigations of bubble behaviors and heat transfer performance on micro/nanostructure surfaces

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ABSTRACT

The multi-level hierarchical surfaces combining different characteristics of single modified surfaces such as expanded heat transfer area, nucleation site density and capillary wickability can further enhance the heat transfer performance. The pool boiling experiment of FC-72 with 35 K subcooling was conducted on the hybrid micro/nanostructure surface (NPF50-60) with nanoforest structure fabricated on the top and bottom of micro-pin-fins using the dry etching and plasma repolymerization techniques. As a comparison, experiments were also conducted on the smooth surface (S), the micro-pin-finned surface (PF50-60) and the nanoforest surface (NS). The novel phenomenon of bubble oscillation on heating surface was observed, which is considered as the result of interactions between evaporation and condensation effects. The predictions of bubble center position during oscillation from forces analysis agree well with the experimental results. In addition, the bubble jumping induced by coalescence was also observed. The results indicated that the three micro/nanostructure surfaces can significantly enhance the boiling heat transfer performance compared to the smooth surface. The lower wall superheat and greater heat transfer coefficient (HTC) with relatively large critical heat flux (CHF) were achieved on the hybrid micro/nanostructure surface for the larger cavity size of nanoforest structure. The wicking velocity of different surfaces obtained from the capillary wickability tests shows a good linear relationship with the CHF. It was concluded that the mechanism of CHF enhancement on micro/nanostructure surfaces is the liquid replenishment with capillary wickability to prevent the expansion of dry spots and maintain a higher critical heat flux.

1. Introduction

Boiling, as an efficient heat transfer method for its extremely high heat transfer coefficient compared with conduction and convection, is widely used in various heat dissipation systems such as electronic devices, heat exchangers, refrigeration equipment and so on. However, the heat transfer capacity of boiling heat transfer is limited by the upper cooling limit critical heat flux, where the transition from nucleate boiling to film boiling results in a sharp decrease in the heat transfer coefficient. Therefore, many researchers have focused on the critical heat flux enhancement in recent years.

Surface modifications like expanding the heat transfer area, increasing the nucleation site density, changing the wettability and prompting capillary wickability are effective and economical methods. The main surface modification methods include the porous coatings and structures of various sizes fabricated on the heating surface. Wu et al. [1] reported that a layer of 1 μm thick TiO_2 nanoparticles coating on the copper surface could significantly improve the CHF of water and FC-72, which was considered as the combined effects of the increased nucleation site density and improved wettability. Kwark et al. [2] believed that the hydrophilicity and the higher wicking velocity of the nanocoatings promoted the rewetting effect of the liquid on the heating surface and improved the CHF. Hsu et al. [3] covered the copper surface with silica nanoparticles to change the surface hydrophilicity. The results showed that CHF increased with decreasing the contact angle. Ahn et al. [4] deposited graphene films of different thicknesses on silicon wafers. The CHF increased with the increase of the thickness until the thickness was about 150 nm, which was explained that the graphene with higher thermal conductivity inhibited the formation of hot spots, thereby increasing the CHF. Dharmendra et al. [5] showed that carbon nanotubes (CNTs) deposited on the copper surface could reduce the onset of nucleate boiling temperature and improve CHF because of the

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high thermal conductivity and fin effect of CNTs. Forrest et al. [6] demonstrated that the nanoparticle thin-film coatings fabricated by a layer-by-layer self-assembly method can effectively improve CHF and the chemical composition and surface morphology of the coatings had a profound effect on the boiling heat transfer performance. Takata et al. [7] reported that the TiO_2 coating showed superhydrophilicity after exposing to UV light, which increased the CHF by 200%. Phan et al. [8] deposited different nanoparticles on stainless steel surfaces to obtain different contact angles. The results showed that the wettability had a great influence on the boiling heat transfer performance. Guglielmini et al. [9] conducted saturated pool boiling experiments of FC-72 on millimeter fin arrays, which significantly improved CHF compared to the smooth surface. Wei and Honda [10] found that at the FC-72 subcooling of 45 K the CHF of micro-pin-fin structured surfaces can reach as much as 4.2 times of the smooth surface. Jung et al. [11] investigated the effects of submicron-scale roughness on the subcooled boiling heat transfer in FC-72, which could increase the nucleation site density and heat transfer area to improve the HTC and CHF. Klausner et al. [12] studied the effect of the size and spacing of the novel "hoodoo" structures on CHF enhancement. Chen et al. [13] fabricated Si and Cu nanowire surfaces, which could greatly improve the CHF compared to the smooth surface due to the higher nucleation site density and stronger capillary pumping effect. Lu et al. [14] found that both the liquid spreading and the heater size could affect CHF of saturated boiling on silicon nanowires. Demir et al. [15] concluded that a shorter length of the silicon nanorod could achieve a higher CHF. Kim et al. [16] fabricated nanopillar surfaces with different diameters. It was believed that the capillary wickability could promote the liquid spreading to prevent the heating surface from drying out and increase the CHF. A wickability-CHF model was established, which was in good agreement with the experimental results. Kim et al. [17] conducted boiling heat transfer experiments on twelve different size microstructure surfaces. The results showed that there was an optimum size for the maximum CHF enhancement, which was consistent with the predictions from capillary flow analysis.

With the increase of the power and compactness of electronic devices, the requirement of heat dissipation capacity is higher. However, the traditional single modified surfaces have limited enhancement on the heat transfer performance. Many researchers have proposed that multi-level hierarchical surfaces fabricated by combined techniques can further improve the heat transfer performance. Take the biphilic surfaces for example [18–20]. The hydrophilic surfaces can significantly improve the CHF through the liquid wettability, while the wall superheat is lower on hydrophobic surfaces. Therefore, the hydrophobic dot arrays can be used to promote the nucleation and reduce the wall superheat, and the hydrophilic region provides liquid replenishment and enhances the CHF. As a result, the heat transfer performance is significantly improved on the biphilic surfaces. Besides, the porous micropillars and microchannels fabricated by sintering copper nanoparticles can also improve the boiling heat transfer performance [21–23]. The porous structures between sintered copper nanoparticles have more nucleation sites and an extended surface area to enhance the heat transfer coefficient and meanwhile enhance the capillary pumping effect for the liquid replenishments to increase CHF. With the development of Micro/Nano-electromechanical Systems (MEMS/NEMS) technologies, the fabrication of hybrid micro/nanostructures have been realized. Launay et al. [24] prepared a variety of micro/nanostructure surfaces, which could obviously increase the heat flux under low wall temperature. Rahman et al. [25] fabricated hybrid micro/nanostructures using the tobacco mosaic virus biotemplate, which improved the surface wickability and enhanced CHF. Dhillon et al. [26] conducted saturated pool boiling experiments on hybrid micro/nanostructure surfaces using a deep reactive ion etching technique to fabricate nanograss on micropillars. Compared to micropillar surfaces, the micro/nanostructures could improve CHF greatly with promoting liquid rewettability. Wen et al. [27] considered that the factors improving the CHF were nucleation site density, capillary liquid supply, and separated liquid-vapor pathways on the two-level patterned copper nanowire surfaces. Jaikumar and Kandlikar [28,29] also reported that the heat transfer performance could be enhanced significantly by separating liquid-vapor pathways through selectively depositing a layer of porous copper coating on different regions of the open microchannel surfaces. Lee et al. [30] showed that the nanowire and micro-cavity hybrid surfaces could delay bubble coalescence and enhance CHF.

It can be seen from the above results that the multi-level hierarchical surfaces, which combine different characteristics of single modified surfaces, can further enhance the heat transfer performance through increasing nucleation site density, prompting capillary wickability and so on. Inspired by this idea, the nanoforest structure was fabricated on the top and bottom of the micro-pin-fins to form a hybrid micro/nanostructure surface. The subcooled pool boiling experiments were conducted to obtain the boiling heat transfer curves of different surfaces, which included the smooth surface, the nanoforest surface, the micro-pin-finned surface and the hybrid micro/nanostructure surface. The bubble behaviors and liquid spreading on different surfaces were observed with the aid of a high-speed camera. The results show that the hybrid micro/nanostructure surface can significantly reduce the wall superheat and increase heat transfer coefficient with relatively high critical heat flux compared with other single modified surfaces.

2. Experimental apparatus and process

2.1. Surface preparation and characterization

P-doped N-type square silicon chips (10 mm × 10 mm × 0.5 mm), on which three different micro/nanostructures were fabricated, were used as the test surfaces. Micro-pin-fins were fabricated on the silicon chip by using the dry etching technique. The fins are 50 μm thick and 60 μm high and the fin pitch is 100 μm (denoted as PF50-60). The nanoforest surface (denoted as NS) was fabricated by using the plasma repolymerization technique [31,32] as shown in Fig. 1. O_2 plasma treating was applied to the polyimide layer to synthesize nanofibers with small diameters and also the nanofiber bunches. Then the self-generated nanofibers were further utilized as nanomasks in the anisotropic Si etching to form nanoforests. The nanoforest structure was fabricated on the top and bottom of the micro-pin-fins based on PF50-60 with the aid of the plasma repolymerization technique, which formed the hybrid micro-nanostructure surface (denoted as NPF50-60). The SEM (scanning electron microscope) images of the three different micro/nanostructure surfaces are shown in Fig. 2. The laser confocal microscope OLS4000 was used to measure the line roughness of the three micro/nanostructure surfaces. The line roughness of NS, PF50-60 and NPF50-60 are 0.247 μm, 1.014 μm and 2.595 μm respectively. The surface topographies of these structures were also obtained from the laser confocal microscope, which are shown in Fig. 3.

2.2. Pool boiling experimental apparatus and experimental procedure

The pool boiling experimental device is shown schematically in Fig. 4. The test vessel was made from transparent polycarbonate with the size of 100 mm × 100 mm × 100 mm and filled with about 1 L air-dissolved FC-72. A 3 L rubber bag was connected to the test vessel and used to maintain an atmospheric pressure. A 200 W cartridge heater and a copper pipe connected with a water cooler were inserted in the test vessel to control the subcooling of 35 K. The temperature of the bulk liquid was measured with a T-type thermocouple. The bubble behaviors during boiling were recorded with the high-speed camera (Nac Memrecam HX-6E, 2000 fps). The chip heating section is illustrated in Fig. 5. The silicon chip was Joule heated by a direct current through two 0.25 mm diameter copper wires which were soldered on the two opposite sides of the chip respectively. In order to ensure the ohmic contact between the semiconductor silicon chip and the copper