



Enhanced boiling heat transfer on composite porous surface



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ABSTRACT

Composite porous surfaces were prepared to investigate the saturated pool boiling of de-ionized water. Scanning electron microscope (SEM) micrographs showed that the porous layers contains three types of structures, including macro pores above 200 μm diameter, micro pores around 2 μm diameter and dendritic structure around 400 nm diameter. Results showed that, the thickness of the coating layers was 33 μm , 84 μm , 156 μm and the contact angle of de-ionized water against the porous surface reduced with the increase of the coating thickness (35°, 8° and 0°). The highest porosity of the coating layers was 94.4%. The experimental results of pool boiling heat transfer indicated that the critical heat flux (CHF) increased with surface wettability and coating thickness, while the effect of the surface wettability on nucleate boiling heat transfer was complicated. The highest CHF of the porous surface was 239 W/cm^2 , which is 101% higher than that of plain surface. High speed photography was used to observe the bubble behaviors in order to investigate the mechanism of enhanced nucleate boiling. Visualization data indicated that the coalescent bubble on porous surface grew more quickly and the bubble size was larger than that on plain surface under high heat flux range. Consequently, the departure of bubble brought more liquid replenishment, and thus to obtain the continuous rise of heat transfer coefficient and higher CHF value.

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1. Introduction

It is urgent to find effective high-heat-flux removal techniques due to that the energy consumption is a momentous embarrassment to limit the development of electronic industry due to the advent of high-density electronic components. Phase change cooling technique is one of the most powerful cooling solutions for high-heat-flux removal due to its high heat transfer rates. However, broader applications of two-phase change heat transfer are restrained by the critical heat flux (CHF), which determines the maximum power density that could be handled by a boiling heat transfer device. Among the affecting factors of the CHF, surface morphology and wettability have been identified as the key factors. Controlling the surface characteristics would in turn provide new opportunity in CHF enhancement.

Previous studies [1–4] have identified surface morphology as one of the key factors affecting the CHF. Significant enhancement in the CHF has been reported for the heat transfer surface coated with porous layers. For example, Kubo et al. [1] manufactured four kinds of treated surfaces with combination of two cavity mouth diameter (about 1.6 μm and 3.1 μm) and two number of densities

of the micro-reentrant cavities (81 $1/\text{cm}^2$ and 9600 $1/\text{cm}^2$) by use of microelectronic fabrication techniques. Their results demonstrated that the surface with large mouth diameter and larger number density of micro-reentrant obtained higher CHF. Kim et al. [2] studied the nucleate pool boiling heat transfer enhancement of microporous surfaces coated with 390 μm diameter platinum. Their results showed the microporous coating appears to delay CHF by increasing the convection heat transfer contribution with a subsequent decrease in latent heat (vapor generation) and/or increasing the hydrodynamic stability of the vapor leaving the surface from increased bubble vapor inertia. Li et al. [3] reported pool boiling heat transfer of de-ionized in sintered copper mesh layer with 56 μm wire diameter. Their results demonstrated that the boiling heat transfer coefficient was only related to the exposed surface area and was not affected by the layer thickness, while the CHF was strongly dependent on the layer thickness and increases proportionally with increase in the wick thickness. Mori and Okuyama [4] enhanced CHF by the attachment of a honeycomb-structured porous plate with different thickness (1.2 mm, 5 mm, 10 mm) on a heated surface. As the thickness of the honeycomb porous plate on the heated surface decreased, the CHF increases to 250 W/cm^2 . It should be noted that these studies for the surface morphology affecting CHF were mainly focused on the large-scale porous structure surfaces. Although the large-scale porous

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Nomenclature

| | |
|-------|---|
| D | diameter of the copper sample (m) |
| h | heat transfer coefficient ($W/(m^2 K)$) |
| I | current (A) |
| L_1 | distance between surface and the first thermocouple (m) |
| L_2 | distance between two thermocouples (m) |
| q'' | heat flux (W/m^2) |
| T | temperature (K) |
| u | uncertainty |
| U | voltage (V) |

| | |
|---------------|---------------|
| Greek symbols | |
| θ | contact angle |

| | |
|------------|-----------|
| Subscripts | |
| w | wall |
| f | fluid |
| loss | heat loss |

structure surface can effectively increase CHF due to its higher active nucleate site and extended surface area, the wettability of these large-scale porous structure surfaces is not met to the need of further improvement. The surface wettability is another key factor affecting CHF. Surface with high wettability has been identified to enhance phase change heat transfer [5]. The wettability of a surface can be tuned by changing its surface morphology. Recently, the nano-scale surface is boomed in changing the surface morphology.

For instance, Zhang and Kim [6] proposed a three dimensional, interconnected alumina nano porous surface (ANPS) using an anodic oxidation process. Electrochemical impedance spectroscopy was utilized to study the quantitative evaluation of liquid uptake. Their results demonstrated that the CHF augment trend is well matched with the amount of liquid absorbed into the porous media. Kim et al. [7] prepared artificially nano-scale surfaces with arrays of ZnO nanorods. The contact angle of the nanorods surface against the water was less than 5° . Experiment results revealed that the nanorods surface could increase CHF significantly. Lu et al. [8] used Si nanowire coated-surface with a zero contact angle obtained by wafer-scale electroless etching to enhanced boiling heat transfer. They presented that the Si nanowire array coated surface has a higher CHF than the plain Si surface due to its better liquid spreading. Chen et al. [9] reported a twofold enhancement in CHF on Cu and Si nanowire arrays presumably because of a large capillary force provided by the nanowire arrays.

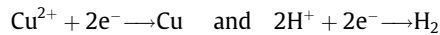
In this work, we prepared the composite structure surface combining the high nucleation site density of the large-scale structure surfaces and the high wettability of the nano-scale structure surfaces to enhance phase change heat transfer. Pool boiling heat transfer experiments with de-ionized water at atmospheric pressure were performed both on the composite structure surfaces and the plain surface to contrast the heat transfer performance. The measured parameters were bubble departure diameter and nucleation density through high-speed photographic. The ultimate goal was to use the data to get a deeper insight to the heat transfer results.

2. Preparation and characterization of the composite porous surface

The composite porous copper surfaces were prepared by an electrochemical method [10]. This type of porous surface has been used extensively in different applications such as catalysis, molecular sieves, fuel cells, sorption and separation. Li et al. [11] fabricated a well-ordered 3D macro-porous metallic surface layer with nanostructured porosity by the electrochemical method, and pool boiling heat transfer experiment with R134a indicated that the heat transfer coefficient is enhanced over 17 times at $1 W/cm^2$ compared to a plain reference surface. The overpotential [12], electrolytic solutions [13], additive [14], deposition time [15]

and electrolytic process [16] have been researched to improve the preparation technology.

In the preparation process, copper rod sample with 12 mm diameter was placed as cathode in the electroplating solution which consisted of 0.4 M $CuSO_4$ and 1.5 M H_2SO_4 . Phosphor copper plate with 40 mm length and 40 mm width was placed 20 mm higher than the copper sample serving as anode. Two simultaneous reduction reactions for the Cu^{2+} and H^+ ions in the electrolyte solution happens at the cathode as soon as the electric current was supplied to the electrochemical deposition cell:



Other than most of traditional deposition cases, the hydrogen formed at a much higher rate in our cases. The rapidly generated bubbles partly occupied volume of the copper deposit sediment, leaving a porous surface with multi-scale structure. A series of porous surfaces were prepared under different deposition time. Table 1 listed the characteristics of these porous surfaces. The mass and thickness of the porous layer almost linearly increased with the increment of the deposition time. Static contact angle of 5 μL de-ionized water at the room temperature (about $25^\circ C$) were measured by the Contact Angle Meter JC2000D2 (Shanghai Zhongchen Digital Technology Apparatus Co., Ltd.) on the porous surfaces and plain surface. The plain copper surface was sanded by 1600 mesh paper and the arithmetic mean surface roughness was $1 \mu m$. Experimental results manifested that the contact angle of the plain surface, P1 surface, P2 surface was 81° , 35° and 8° , respectively. The images of contact angle were shown in Fig 1. The contact angle of the P3 surface was considered as 0° because the de-ionized water spread out immediately once it contacted the porous surface [17,18]. Therefore, the P3 surface was of super-hydrophilic characteristic and the contact angle could not represent its wettability completely. The liquid spreading ability is another momentous factor that represents surface wettability for the super-hydrophilic surface [17]. Shirazy et al. [19] develop a new method to compare the wettability of super-hydrophilic surface by measuring time-of-spreading of a droplet.

SEM micrographs indicate that three types of structure were included in the porous layer: macro pores above 0.2 mm diameter, micro pores around $2 \mu m$ diameter and dendritic structure around 400 nm diameter, as shown in Fig. 2. Both the macro pores above 0.2 mm and micro pores can be active nucleation site at appropriate surface superheat in our pool boiling experiment according

Table 1
Characteristics of the porous surfaces.

| Number | Deposition time/s | Mass/mg | Thickness/ μm | Porosity (%) | Contact angle ($^\circ$) |
|--------|-------------------|---------|--------------------|--------------|----------------------------|
| P1 | 10 | 2.8 | 33.2 | 91.6 | 35 |
| P2 | 20 | 5.3 | 84.2 | 93.7 | 8 |
| P3 | 40 | 8.77 | 156 | 94.4 | 0 |

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