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Wettability modification to further enhance the pool boiling performance of the micro nano bi-porous copper surface structure

Ya-Qiao Wang, Jia-Li Luo, Yi Heng, Dong-Chuan Mo *, Shu-Shen Lyu

School of Chemical Engineering and Technology, Sun Yat-sen University, Guangzhou, Guangdong, China
Guangdong Engineering Technology Research Centre for Advanced Thermal Control Material and System Integration (ATCMSI), Guangzhou 510275, China

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ABSTRACT

Boiling heat transfer is widely used in industry and in daily life and it can be enhanced by micro/nano surface modification. Herein, we study the pool boiling characteristics of the micro nano bi-porous copper surface with optimal cavity size from other researchers and present an efficient way to further enhance its boiling heat transfer performance by wettability modification of enlarging the particle size to lower the surface energy. In this work, two micro nano bi-porous copper surface samples were prepared and compared with conventional surfaces. One is the original micro nano bi-porous copper surface (Sample#O) prepared using the hydrogen bubble template deposition method to form abundant pores in optimal cavity size, and the other one is the modified micro nano bi-porous copper surface (Sample#M) that is modified by applying a low current density on Sample#O for a few minutes. Scanning Electron Microscope (SEM) images show that Sample#M keeps the pore size but enlarges the nano dendrite on the top of pore wall to micro balls. The conducted pool boiling experiments indicate that both micro nano bi-porous copper surfaces have superior heat transfer coefficients than the plain copper surface, and the high-speed camera shows that the micro nano bi-porous copper surfaces have shorter bubble growth periods than those surfaces with pure nano structure or pure micro structure. At a heat flux of 90 W cm^{-2}, the heat transfer coefficient of Sample#O is 13 W cm^{-2} K^{-1}, which is 2.8 times over that of the plain surface. Compared to Sample#O, Sample#M can further enhance the pool boiling heat transfer. At the same heat flux of about 90 W cm^{-2}, the heat transfer coefficient of Sample#M is 23 W cm^{-2} K^{-1}, which is 1.7 times over that of Sample#O and 4.8 times over that of the plain surface. The heat transfer coefficient of Sample#M can be as high as 30 W cm^{-2} K^{-1} when it reaches the CHF. High-speed camera images show that highest bubble growth period for Sample#M is just less than 20 ms, which is shorter than that of Sample#O having a value in between 20 ms and 40 ms. It confirms that Sample#M after wettability modification has a lower interface energy which can accelerate the bubbles departure, and has an even more superior heat transfer performance than Sample#O.

1. Introduction

Boiling heat transfer is widely used in industry and in daily life, such as heat exchangers, air conditioners, heat pumps, refrigeration machinery and so on. Generally speaking, there are two common ways to enhance pool boiling. One way is to modify the working fluid, such as to add nano particles [1,2] or to add surfactant [2–4]. The other way is to modify microgeometry or/and wettability of the boiling surfaces.

The micro geometry of boiling surface strongly influences the boiling heat transfer. Traditionally, surface modification can be done by machining [5], sintered metal powders [6], covered mesh [7], etc. Wei and Honda [5] used different silicon chips with micro-pin-fins to enhance the pool boiling of FC-72. Li and Peterson [7] used sintered isotropic copper mesh to enhance the pool boiling. Xu and Zhao [8] enhanced boiling heat transfer by gradient porous metals in saturated pure water.

With the progress in nano technologies, surface modifications with nano structure have been used to enhance boiling heat transfer. Li et al. [9] found “unexpected enhancements” in boiling performance by using copper nanorod structure on copper substrate. Yao et al. [10] prepared 35 μm-tall SiNW nanowire that yielded a heat flux of 134 W cm^{-2} at 23 K wall superheat, about 300% higher than that of a plain Si surface at the same wall superheat. Chen et al. [11] fabricated a surface with TiO_2 nanotube

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* Corresponding author at: School of Chemical Engineering and Technology, Sun Yat-sen University, Guangzhou, Guangdong, China.

E-mail address: modongch@mail.sysu.edu.cn (D.-C. Mo).

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Nomenclature

A	the projected area of porous structure (cm^2)
h	heat transfer coefficient (W cm^{-2} K^{-1})
F_s	starting frame number
F_e	ending frame number
K	permeability (m^2)
k_{Cu}	thermal conductivity of pure copper (W m^{-1} K^{-1})
m	mass of porous structure (mg)
q	heat flux (W cm^{-2})
Q_{su}	total heat supplied by heaters (W)
Q_{loss}	heat loss (W)
R_{eff}	effective pore radius (m)
ΔT	superheat (K)
t	time (s)
T	bubble growth period (s)
T_1	temperature of thermocouple (T1) (°C)
T_2	temperature of thermocouple (T2) (°C)
T_3	temperature of thermocouple (T3) (°C)
T_s	temperature of surrounding (°C)
T_w	temperature of the bottom of porous coating (°C)
x	distance between the thermocouple (T1) and the boiling surface (m)
y	liquid rising height (m)

Greek symbol

σ	liquid surface tension (N m^{-1})
ξ	constant number
ρ	density of pure copper (g/cm^{-3})
θ	contact angle (°)
Φ	porosity of porous structure
μ	viscosity of the liquid (Pa s)
δ	thickness of porous structure (μm)
γ_s	surface energy of solid surface (J m^{-2})

Subscripts

Cu	copper
su	supplied heat
loss	heat loss
eff	effective
w	wall

Abbreviation

CHF	critical heat flux (W cm^{-2})
HTC	Heat transfer coefficient (W cm^{-2} K^{-1})
FR	frame rate (fps)

arrays, and found it could enhance the pool boiling heat transfer compared to the pure Ti metal plate.

Researchers recently found that surfaces with both micro and nano porous structure have superior boiling heat transfer performance than those with only pure nano structure or pure micro structure. Nagato [12] found that the heat flux at the same superheat increased in the order flat surface < nanostructure < microstructure < nano/micro composite structure. Li et al. [13] reported 3-D porous interconnected foam-like structures using hydrogen bubble dynamic template method, and the HTC is about 17 times of plain copper at 1 W/cm^2 when R134a is used as working fluid. Similar works were reported by different researchers. El-Genk et al. [14] deposited micro-porous copper structure in copper sulfate solution which showed an excellent boiling heat transfer coefficient of PF-5060. Patil et al. [15] developed a two-step electro-deposition process to prepare cauliflower-like micro structure, the superheat of pool boiling of saturated distilled water is only about 7 °C when CHF is about 1400 kW/m^2. Xu et al. [16] prepared composite porous surface and the highest CHF of the porous surface was 239 W/cm^2, which is 101% higher than that of plain surface. Wang et al. [17] fabricated micro nano-porous copper surfaces, and found that the sample with multi-layer has lower wall superheat than that of the one with mono-layer, own to its better liquid accommodation from the morphology structure at high heat flux. Ji et al. [18] fabricated several 3D porous coating surfaces with significant heat transfer enhancement, and the sample (TS#7) significantly increases the critical heat flux, which can be 3.7 times that of the plain surface. Kandlikar et al. [19] deposited coatings at the top of micro channels to gain a heat transfer coefficient as high as 2900 kW m^{-2} K^{-1}. Li et al. [20] manufactured modulated porous structure and the highest heat transfer coefficient reached 450 W/cm^2, over 3 times that of a plain copper surface. Wang et al. [21] fabricated copper vertical micro dendrite fin arrays which can increase the heat transfer coefficient about 260% compared to that of the plain copper surface.

In order to optimize the structure of micro nano-porous material to get a better heat transfer performance, it is worth revealing the effects of different structural scale on the boiling heat transfer. Dong et al. [22] analyzed the surface-microstructural effects on heterogeneous nucleation in pool boiling and found that the effect of microstructures greatly enhanced the nucleation of bubbles when the curvature radius of these microstructures is in the range of 5–100 times less than the bubble radius. Dong et al. [23] presented that microstructures can enhance bubble nucleation to reduce the wall superheat and enhance heat flux, while nanostructures can accelerate bubble departure. Li et al. [9] calculated the range of active cavity size as a function of wall superheat, and indicated that the optimal range for cavity size, in which the wall superheat can be even as low as 2 °C, is in the range between 10 μm and 100 μm.

The surface wettability is also important for bubble dynamics in nucleation boiling. Fritz et al. [24] and Wen et al. [3] found that the surfaces with smaller contact angle has smaller bubble diameter and can enhance nucleation pool boiling. On the contrary, Phan et al. [25] observed that the hydrophilic surface with smaller contact angle has larger departure bubble diameter. Recently, researchers found that wettability patterned surfaces (or the biphilic surfaces) have much better boiling heat transfer performance than merely hydrophilic or hydrophobic surface [26–29]. Betz et al. [26] observed that hydrophilic networks featuring hydrophobic islands has better heat transfer performance than the hydrophilic surface, due to the hydrophobic islands can enhance the nucleation and the hydrophilic networks efficiently prevent the formation of an insulating vapor layer. Other researchers also found that the wettability patterned surface can enhance nucleation density, accelerate bubble growth rate and bubble departure rate, such as Dai et al. [27] functionalized the hydrophobic nanotube with hydrophilic functional group, Jo et al. [28] spatially patterned self-assembled monolayers (contact angle 81°) on the head of Si micro posts (contact angle of plain Si is 57°), Zupancic et al. [29] manufactured hydrophobic polydimethylsiloxane-silica coating on laser induced superhydrophilic steel surface, et al.

In this work, we try to fabricated micro/nano bi-porous surface combining both optimal cavity size and wettability modification. Firstly, we fabricated a micro nano bi-porous copper surface with abundant micro pores whose diameters are in the optimal range for cavity size according to previous study from other researchers [9]. Secondly, a prior development by wettability modification is