International Journal of Thermal Sciences 130 (2018) 47–58

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Experimental investigation on enhancement of nucleate pool boiling heat transfer using hybrid wetting pillar surface at low heat fluxes

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ARTICLE INFO

Keywords:
hybrid wetting surface
Heat transfer coefficient
Nucleate pool boiling
Orthogonal array experiment
Pillar surface

ABSTRACT

Hybrid wetting surfaces have the significant potential to enhance the performance of boiling heat transfer. In this paper, the hybrid wetting surfaces with pillars in millimeters are fabricated by the chemical deposition approach. Next the heat transfer coefficients for these fabricated surfaces are measured in nucleate pool boiling heat transfer experiment at low heat fluxes ranging from 3.75 to 18 W/cm^2. Under the same geometric size and heating power conditions, it is found that the heat transfer coefficients of the hybrid wetting surfaces are higher than the values of the spatially uniform wetting surfaces, regardless of hybrid modes. Additionally, the enhancement performance of boiling heat transfer among the hybrid wetting surfaces with different geometric sizes are distinctly different. Finally, the orthogonal array experiments relating to influential factors including wetting modes and geometric factors of the pillar surfaces are implemented, and further reveal the effects of the combination of these various influential factors on the performance of nucleate pool boiling heat transfer.

1. Introduction

Boiling is an effective heat transfer approach for the phase changed heat exchanging equipment in daily life and in industry. Although the boiling heat transfer coefficient(HTC) is typically one order of magnitude higher than the single-phase forced convection, a lot of new enhanced heat transfer techniques are required to promote the performance of boiling heat transfer [1–5]. Among the impacting factors for the performance of boiling heat transfer, the wetting feature of the heating surface is crucial, since it directly influences the generating bubbles in many aspects, including nucleation sites, nucleation densities, growing radiuses, departure times, etc. These characteristics of bubble generation have a direct impact on two significant evaluating parameters for the pool boiling performance, i.e., heat transfer coefficient(HTC) and critical heat flux(CHF) [6–12].

For the spatially uniformly heating surface, there are different strategies to adjust wettability of the surface to promote the boiling heat transfer performance [13,14]. In the low heat flux nucleate boiling regime, reduction of the surface wettability(i.e., increasing the apparent contact angle of water or other working media on the surface in air) can promote nucleation, which results in increments of the HTC. However, in larger heat flux nucleate boiling, reduction of the surface wettability would limit the number of active nucleation sites due to the larger contact diameter of the bubbles on the surface [6,7]. Compared with the hydrophobic(HPo) surface at the same values of wall superheat, hydrophilic(HPi) surfaces can produce smaller and less bubbles. This feature of the hydrophilic surface guarantees that there are sufficient spaces for large quantities of nucleation bubbles to grow. These bubbles on hydrophilic(HPi) surface can grow independently and don't coalesce with each other to form the larger bubble or even gas film. Therefore at high heat fluxes, increments of surface wettability(i.e., reducing the apparent contact angle on the surface in air) can improve liquid transport resulting in promotion of both the HTC and CHF [6,7].

On the basis of the characteristics of HPo and HPi surfaces to enhance boiling heat transfer above, it is reasonably considered that the ideal heating surface requires both hydrophobicity mode to promote nucleation and hydrophilicity mode to suppress individual bubble excessive growth. Obviously, the surface with spatially uniform wettability can't satisfy these two requirements above simultaneously.

In nature, the hybrid wetting surface, e.g., the bumpy surface covered on the back of some beetles in the Namib Desert, can enhance the water capture [15–17]. Inspired by this hybrid wetting surface in nature, some researchers have started to focus on the hybrid wetting surfaces consisting of both the hydrophilic and hydrophobic patterns, and investigated whether this hybrid wetting surfaces can enable promotion of the HTC and CHF simultaneously. Herein, Betz et al. [6] demonstrated that macroscopically smooth and flat hybrid wetting surfaces combining hydrophilic and hydrophobic patterns, e.g.,

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https://doi.org/10.1016/j.ijthermalsci.2018.04.011
Received 20 September 2017; Received in revised form 29 January 2018; Accepted 9 April 2018

Nomenclature

D_g	Goove depth(m)
h	heat transfer coefficient(W/m^2·K)
H_{ji}	the sum of values of HTCs corresponding to the *i*-th level of the *j*-th factor in orthogonal array experiment
$\overline{H}_{ji}$	average value of H_{ji}
K_{Cu}	conductivity of the pure cooper(W/m·K)
R	range in orthogonal array experiment
q	heat flux(W/m^2)
T_{int}	local temperature of the liquid-vapor interface
T_{sat}	saturation temperature
t	time(s)
t_g/t_w	bubble growing and waiting times
T	temperature(K)
W_g/W_r	Groove width/Rib width(mm)
Δx_1	$/\Delta x_2/\Delta x_3$ distance between K thermocouples in cooper heating cylinder

Greek symbols

θ	apparent contact angle

Subscripts

g	groove
r	rib
sat	saturation
wall	wall surface

hydrophilic surface with isolated hydrophobic islands, can effectively improve pool boiling performance, and the measured CHFs and HTCs for this hybrid wetting surfaces are 65% and 100% higher than that for the hydrophilic surface with 7° wetting contact angle. After several years, Betz et al. [7] manufactured the first “superbiphilic” surfaces i.e., super-hydrophilic surface with isolated super-hydrophobic islands, and this hybrid wetting surface showed exceptional performance in pool boiling, of which the highest CHF is over 100 W/cm^2 and the highest HTC is over 100 kW/(m^{2}K).

As one kind of special gradient wetting surface [18–24], the hybrid wetting surface has the potential to promote the performance of boiling heat transfer. However, to the authors' knowledge, until now there have been few application examples of boiling heat transfer enhancement using hybrid wetting surfaces in practical heat exchange equipment. The fabrication approaches should be one significant factor to limit the practical application of the hybrid wetting surface. To date there have been only a few hybrid wetting fabrication examples introduced in the published research literature. Herein, Betz et al. [6,7] introduced the steps to fabricate the hybrid wetting surface which was flat on a macroscopic scale, by the standard photolithography techniques. Hou et al. [17] showed the hybrid wetting pillar surface consisting of hydrophilic pillar arrays and surrounding hydrophobic layer, and it was produced by the craft combined with standard photolithography, oxide etching, and modified deep reactive ion etching (DRIE). This hybrid surface could enhance the condensation heat transfer.

For a practical heat exchanging surface, enhancing heat transfer techniques are generally adopted to promote the performance of the heat exchange, for example using bumpy surfaces with many extra convex spheres, squares or cylinder ribs in millimeters or even bigger, etc., as the heat exchange surface instead of a purely flat surface. In general, these enhanced heat transfer surfaces have uniform wettabilities. In this work, the hybrid wetting enhanced heat transfer surfaces with square-pillar in millimeters are manufactured by the chemical deposition method, which is similar to the hybrid wetting wings of the Namib desert beetle [15]. Next, it is investigated that whether they can promote the performance of the nucleate pool boiling heat transfer at low heat fluxes, just as the spatially flat hybrid wetting surface fabricated in Refs. [6,7]. Finally, the standard orthogonal array experiments relating to influential factors including wetting modes and geometric parameters of the square-pillar surfaces are implemented, and further reveal the effects of the combination of these various influential factors on the performance of nucleate pool boiling heat transfer.

2. Materials fabrication and experimental method

2.1. Surface design and fabrication

The sketch of the bumpy surface with square pillars is shown in Fig. 1. The micro square pillars in millimeters were shaped using the wire cutting technology on one entire 40 × 40 × 10 mm (length × width × height) copper block. A DK7732 CNC(Computerized Numerical Control) wire cutting machine was used. The diameter of molybdenum wire used was 0.18 mm and the surface roughness after manufactured should be less then 2.5 μm according to this machine manual. The processing precision of this machine is 0.015 mm which can satisfy the requirement for the millimetric square pillars.

After the wire cutting process, the test pieces were cleaned with acetone, ethyl alcohol and hydrochloric acid solutions under ultrasonic conditions, respectively. Then the test pieces were dried out in the dry nitrogen atmosphere. One piece of the pure copper micro-pillar test sample is shown in Fig. 2. Fig. 3 shows macroscopically smooth and clean copper block surface as the experimental representative surface, which was also processed by the same wire cutting craft. In this work, the pillar size on the square-pillar surface is of the same order of the magnitude as the diameter of the testing water droplet, so all the contact angle in the following text were tested on the representative cooper surface instead of the square-pillar surface. It should be noted that the slender trace lines were left on the macroscopically smooth copper block surface after wire cutting.

As shown in Fig. 4, the average static contact angle of the clean flat representative copper surface above in Fig. 3, is $\theta = 76°$ tested by video optical contact angle measurements(OCA20). Due to the adoption of same wire cutting craft, it is reasonable to consider that the static contact angle of each face on the pillar test piece after wire cutting as shown in Fig. 2, including the faces surrounding the square pillar and the additional bottom base face, should be the same as the value of the contact angle of the flat representative copper surface, i.e., $\theta = 76°$.

The chemical deposition approach was utilized to produce the

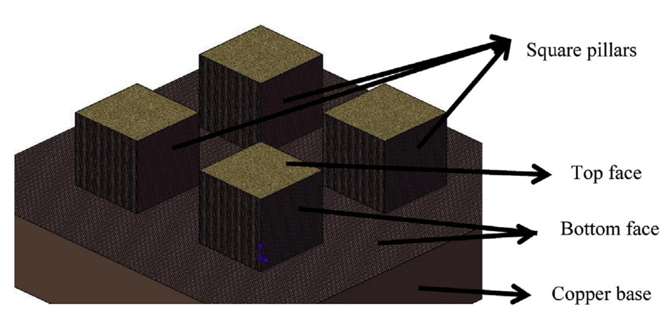

Fig. 1. Sketch of magnified structure of part of square-pillar heating surface.