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Pool boiling heat transfer of FC-72 on pin-fin silicon surfaces with nanoparticle deposition

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ABSTRACT

In the present study, two types of micro-pin–fin configurations were fabricated on silicon surfaces by a dry etching method, i.e., staggered pin fins (#1) and aligned pin fins with empty areas (#2). The micro-pin–fin surfaces were then further modified by depositing FeMn oxide nanoparticles (~35 nm) electrostatically for 8 h and 16 h, respectively, namely #1-8h, #1-16h, #2-8h and #2-16h. Subcooled pool boiling heat transfer was experimentally studied on these surfaces at atmospheric pressure, using FC-72 as the working fluid. The results showed that in comparison to the smooth surface, pool boiling heat transfer was significantly enhanced by the micro-pin-fin surfaces and the maximum superheat was considerably decreased. Additionally, critical heat fluxes were also greatly improved, e.g., the critical heat flux on #1 was almost twice of that on the smooth surface. Generally, the nanoparticle deposition could further enhance pool boiling heat transfer, including the heat transfer coefficient and critical heat flux (CHF). High speed visualizations were taken to explore the mechanisms behind the heat transfer performance. The bubble behavior on the micro-pin–fin surfaces with and without nanoparticles was compared at low, moderate and high heat fluxes, respectively. The wickability of FC-72 on the test surfaces was measured, based on which, a modified CHF model was proposed to predict the experimental CHFs. Accordingly, a possible mechanism of CHF enhancement was described.

1. Introduction

Surfaces with high heat flux exist in nuclear reactors, supercritical boilers, high-power LEDs and supersonic aircraft combustion chambers etc. High-efficiency cooling technologies are required in these applications. Compared with single-phase heat transfer, boiling heat transfer is a potential way to dissipate high heat fluxes due to higher heat transfer coefficients, e.g., $O(h) \sim 0.1$–$10\ W/cm^2\,K$ for water [1]. In the 1950s–1960s, boiling heat transfer was studied extensively due to the development of nuclear power generation. Many semi-theoretical and semi-empirical models were set up then, e.g., the Rohsenow correlation (1952) and the Zuber correlation (1955) for nucleate boiling and critical heat flux, respectively, and the Chen correlation (1963) considering convective boiling [2]. During the 1980s–1990s, the microelectronic industry grew up, which stimulated the development of chip cooling. For most electronic chips, it is of great importance to keep the temperature relatively constant and below 85 °C [3] and boiling heat transfer has been proved to be effective to achieve this [4]. Accordingly, it is essential to enhance its performance. Surface modification can increase the number of active nucleation sites, improve the wettability and modulate bubble behavior etc. Therefore, this is an effective way to enhance boiling heat transfer. To date, numerous surface modification technologies have been applied, e.g., mechanical maching techniques, surface coating techniques and chemical processing [3].

Surfaces with microstructures like microchannels, micro pin fins, micro pillars and microporous coatings have been widely studied. Tang et al. [5] developed porous interconnected microchannel nets using microfabrication techniques. Experimental results showed that these structures exhibited a lower incipient superheat and higher *HTC* than the solid interconnected microchannel nets. Honda et al. [6], Wei and Honda [7] and Wei et al. [8] carried out systematic studies on the pool boiling of FC-72 on square micro-pin-fin silicon surfaces, e.g., the effect of dissolved gas, subcooling and size of the pin-fins. The results

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Nomenclature

A	chip surface area, (m^2)
A_w	wetted area, (m^2)
CHF	critical heat flux, (W/m^2)
h	the height of a micro-pin-fin, (m)
Δh	liquid height drop, (m)
HTC	heat transfer coefficient, ($W/m^2{\cdot}K$)
I	current (A)
L	length of the sides of chips
p	the pitch between two neighboring micro-pin-fins
q	heat flux, (W/m^2)
SS	smooth surface
t	time, (s)
T	temperature, (K)
ΔT_{sub}	subcooling, (K)
U	voltage, (V)
V'	absorbed flow rates, (m^3/s)
w	the width of a micro-pin-fin, (m)
Greek symbols	
μ	dynamic viscosity, Pa·s
ρ	density, kg/m^3
σ	surface tension, N/m
Subscript	
bulk	bulk flow
l	liquid
sat	saturated
ss	smooth surface
v	vapor
w	wall

showed that the pin fins could significantly decrease the maximum superheat and increase CHF. Pastuszko [9] investigated pool boiling of FC-72 and water on micro-fin copper surfaces covered with and without wire mesh structures, respectively. At low and moderate heat fluxes, the compound structures provided additional capillary pressure for liquid supply and a larger number of nucleation sites. At high heat fluxes, the mesh structures created additional resistance for vapor escape, which partly may cause a low heat transfer coefficient. Hao et al. [10] employed deformable pin-fin structures for boiling heat transfer of ethanol, water and FC-72. It was found that deformable structures combined the merits of closed-tunnel and open-tunnel, having the best *HTC* and CHF. Sarafraz and Hormozi [11] studied pool boiling of carbon nanotube nanofluids on micro-fin surfaces in which *HTC* and CHF were both enhanced. Gheitaghy et al. [12], El-Genk and Ali [13,14], Jun et al. [15] and Ji et al. [16] studied the boiling on copper surfaces with microporous coatings. The CHF and *HTC* were enhanced considerably. The mechanisms were contributed to the wettability, the number of active nucleation sites, bubble interaction, internal vapor and liquid counter flow patterns, strong convection caused by the agitation of bubbles and capillary evaporation induced by the porous coatings.

With the development of nanotechnology, the effect of nanostructures on boiling starts to attract attentions e.g., electrospraying [17–19], chemical vapor deposition [20,21] and electron beam physical vapor deposition [22,23]. Sumit et al. [17] deposited polymer nanofibers on copper surfaces and tested the pool boiling with HFE - 7300 and DI water. It was shown that the nanofibers generated large amount of small pores, facilitating nucleation. This enhanced pool boiling heat transfer significantly. Compared with DI water, HFE - 7300 has lower surface tension and saturation temperature and the onset of nucleate boiling appears at a smaller superheat. A similar study was also conducted in [19]. Jo et al. [18] controlled the wettability of surfaces by electrosprayed nano-pillars and pool boiling of distilled water was studied. As a result, the CHF and *HTC* were both enhanced and an optimal texturing was identified. Jaikumar et al. [20] studied pool boiling of water on copper surfaces with carbon-based coatings by chemical vapor deposition and discussed the mechanisms behind pool boiling enhancement. It was concluded that the thermal conductivity and wettability were not contributing factors, but the large contact angle hysteresis was seen as a possible mechanism. Pratik et al. [21] investigated the performance of silicon surfaces deposited with foam-like nanomaterials. CHF was considerably increased due to the hydrophilicity of the coating. Das et al. [22,23] deposited silicon oxide nanoparticles and SiO_2 nanosturctures on copper surfaces. It was stated that the incipient superheat of water was decreased. About 58% and 80% enhancement of *HTC* was achieved by silicon oxide nanoparticles and SiO_2 nanosturctures, respectively. Dong et al. [24] compared the performance of silicon surfaces with microstrucutres and nanostructures. The results showed that the surfaces with microstructures had much higher density of active nucleation sites. However, nano-structures can accelerate bubble departure by decreasing bubble diameter, preventing the formation of a vapor blanket at high heat fluxes. Then, Moon et al. [25] designed micro/nano-structure silicon surfaces by depositing nano wires on micro pillars. The results showed that the micro/nano-structure surfaces had higher CHFs. The enhanced CHF was due to better liquid supply. However, it was not quantitatively analysed how large the liquid supply was enhanced. Recently, heterogeneous wettable surfaces were fabricated as well, e.g., hydrophobic patterns on a hydrophilic surface [26,27] and periodic-hydrophobic-hydrophilic surfaces [28]. These surfaces modulated liquid supply and bubble behavior, increasing the performance of boiling.

As reviewed above, micro/nano-structure surfaces should be quite promising in the boiling heat transfer, and the wickability of liquid on surfaces, representing the ability of liquid supply, is crucial for CHF enhancement. Ahn et al. [29] and Rahman et al. [30] provided a quantitative measurement of the wickabiltiy of water on copper surfaces and silicon surfaces, respectively and they proposed CHF models considering the contribution of the wickability to CHF enhancement. However, the quantitative measurement of the wickability of liquids with high wettability e.g., FC-72 is not reported and the CHF models in [29,30] did not consider the effect of subcooling. Therefore, the present study aimed to investigate the boiling on micro/nano-structure surfaces and provide deep insights into the mechanism of CHF enhancement by a quantitative measurement of the wickability of FC-72. In addition, a modified CHF model was proposed, incorporating the contribution of wickability and subcoolijng. In the present study, two types of micro-pin-fin configurations with almost the same area enhancement were designed, i.e., the staggered micro pin fins (#1) and the aligned micro pin fins with empty areas (#2), because these configurations can introduce better capillary performance than the homogeneous configuration. Subsequently, FeMn nanoparticles were deposited on the micro-pin-fin surfaces by an electrostatic deposition method. Pool boiling of FC-72 on these surfaces was experimentally studied at atmospheric pressure at three subcooled degrees, i.e., 15 K, 25 K and 35 K. It should be noted that the present work is totally new compared with our previous work [28]. The configuration of micro pin fins is totally different.