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Enhancement of boiling heat transfer under sub-atmospheric pressures using biphilic surfaces

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ABSTRACT

Surface wettability of a heating surface is one of the most important factors affecting boiling performance. While a biphilic surface (with juxtaposed hydrophilic and hydrophobic regions) is known as a promising technique to enhance water pool boiling at the atmospheric pressure, there is no research regarding its potential for sub-atmospheric applications. In the present study, we have investigated the characteristics of pool nucleate boiling on biphilic surfaces at sub-atmospheric pressures. Biphilic surfaces were made by applying Ni-TFEO (tetrafluoroethylene oligomer) electroplating (with a contact angle of about 140°) on a copper surface. The heat transfer performance of various biphilic surfaces (with different hydrophobic spot diameters and pitches) were measured in the pressure range from atmospheric to 6.9 kPa. At a pressure of 14.0 kPa, the wall superheat at the onset of nucleate boiling was reduced by 12 K on a biphilic surface compared with a mirror-finished copper surface. The experiment with three different biphilic patterns revealed that smaller pitch and diameter of the hydrophobic spots were favorable to heat transfer at 14.0 kPa. The enhancement of HTC over Kutateladze's correlation reached 270%. A sharp transition from continuous to intermittent boiling, resulting in large deterioration of HTC, was observed on a biphilic surface at a much lower pressure than that on a copper surface. Boiling performance was less affected by the pressure level above the transition pressure.

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1. Introduction

Cooling of electronic devices has become more important as the energy consumption associated with thermal management of those devices soars with the increasing power density. For instance, data centers consume 1.3% of the total electricity use in the world in 2010 [1]. Almost 40% of that electricity consumption is used for thermal management of computers in order to maintain their temperatures below the safety limit (≈ 85 °C). There is thus an urgent need for energy-efficient cooling technologies. To meet this demand, phase-change cooling systems, such as heat pipes, are often preferred to conventional air cooling due to the higher heat transfer coefficient (HTC) [2,3]. Amongst the existing technology, two-phase closed thermosyphons (TPCT, or gravity assisted wickless heat pipe) have a higher heat transport capability due to being free of the capillary limit.

Use of water as the working fluid of TPCTs offers several advantages such as non-toxicity, non-flammability, environmental friendliness, and efficient heat transfer due to large latent heat of vaporization [4,5]. However, a reduction of the working pressure is often necessary to keep the saturation temperature below the operational temperature of electronic devices, which is far below the boiling point at the atmospheric pressure. Unfortunately, under reduced pressure conditions, higher wall temperatures are required to activate cavities on the boiling surface. Therefore, the superheat at the onset of nucleate boiling (ONB), ΔT_{ONB}, increases with decreasing pressure. This delayed boiling incipience results in a shift of the boiling curve toward the right-hand side (namely, resulting in a deterioration of HTC) [6]. Moreover, bubble behavior of sub-atmospheric boiling considerably differs from that at the atmospheric pressure. Decreases of the vapor density at lower pressures cause an expansion of the bubble footprint and large departure diameters [7]. A departing bubble rapidly removes a great quantity of heat from the wall, and induces intense motion

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Nomenclature

g	acceleration due to gravity
h	heat transfer coefficient
H	water level
l_a	Laplace coefficient
L_{lv}	latent heat of vaporization
p	pitch
P	pressure
Pr	Prandtl number
q	heat flux
SD	standard deviation
T	temperature
ΔT_{ONB}	wall superheat at the onset of nucleate boiling
ΔT_{sat}	wall superheat
x	position of thermocouple

Greek symbols

θ	contact angle
λ	thermal conductivity
ν	kinetic viscosity
ρ	density
σ	surface tension
φ	spot diameter

Subscripts

c	copper
l	liquid
v	vapor
w	wall

in its wake stripping away the superheated liquid layer. As a result, the generation of the next bubble is suppressed until the surface and adjacent liquid are reheated enough over a duration called the waiting period. Once the superheated state is reached, another bubble nucleates and grows explosively, and then the above cycle is repeated [8,9]. The resulting unstable boiling behavior, called *intermittent boiling*, causes large temperature fluctuations of the heating surface. Such disadvantages of sub-atmospheric boiling could pose threats to electronics cooling where low boiling incipience superheats and stable wall temperatures free of intermittent boiling are preferred in addition to superior HTC.

Incidentally, wettability modifications of the heating surface have been intensively studied as a promising way to enhance boiling heat transfer. Surface wettability is generally divided into two types, hydrophilicity and hydrophobicity, based on the contact angle with water, θ. Hydrophilic surfaces, whose θ is below 90°, can enhance the critical heat flux (CHF) because its high affinity for water promotes liquid supply to the surface resulting in reduced nucleation site density and suppressed bubble coalescence. Takata et al. [10] applied a superhydrophilic surface (that is, $\theta \approx 0°$), made by exposing a TiO_2-sputtered surface to UV irradiation, to pool boiling of water at the atmospheric pressure. CHF of such a surface was enhanced by about two folds compared with that of a non-coated surface. On the other hand, hydrophobic surfaces facilitate bubble generation, which leads to lowered ΔT_{ONB} and improved HTC in the low-heat-flux region. In another work of Takata et al. [11], boiling characteristics of a superhydrophobic surface (with $\theta \geq 150°$) were studied under the atmospheric condition. They found the occurrence of bubble incipience at extremely low superheats—even negative in subcooled conditions—in addition to apparent deterioration of CHF due to uncontrolled bubble expansion and merging. The hydrophobicity and hydrophilicity thus have opposing effects on HTC and CHF. Therefore, careful trade-offs are required in surface design for maximizing boiling performance. Betz et al. [12] successfully combined superhydrophobic and superhydrophilic surfaces by means of coating Teflon fluoropolymer (θ = 150–165°, patterned with photolithography) on a nanostructured silicon wafer (θ = 0°). The resulting hybrid surface, which was named *superbiphilic* surface, significantly lowered ONB (to about 1 K) and improved CHF by more than two folds compared with a smooth hydrophilic surface (θ = 7°). Moreover, the wettability contrast of the superbiphilic surface modified bubble behavior significantly. Specifically, controlled bubble footprint and departure diameter prevailed with the three-phase contact line pinned at the edge of the hydrophobic spots. This pinning effect offers a remarkable enhancement of HTC reaching one order of magnitude at low superheats and about 300% for larger values of superheat.

These interesting findings lead us to the conclusion that the advantages of biphilic surfaces might be used to counteract the drawbacks of sub-atmospheric boiling. Most of the existing boiling studies of biphilic surfaces are limited to the atmospheric condition [13–16], and, to the best of our knowledge, there has been no research of such surfaces to boiling under sub-atmospheric pressures. In the present study, boiling characteristics on biphilic surfaces were investigated under reduced pressures. We compared the heat transfer performance of several biphilic surfaces with different pattern designs (diameter and pitch) at two pressures, $P \approx 102.3$ kPa (atmospheric) and 14.0 kPa, respectively. The latter roughly corresponds to the saturation temperature of 52 °C (see Fig. 1 [17]). Steady state boiling behavior and transient variations of the wall temperature were then obtained over a wide range of pressure. The results show a regime transition from continuous to intermittent boiling, which is dissimilar to that of plain metal surfaces reported previously [6]. It should be mentioned that the present study focuses on only ONB and HTC at low to medium heat fluxes, not on CHF. The remainder of this paper consists of the following parts: in Section 2 the experimental apparatus and procedure are described, including the fabrication process of the heating surfaces. Section 3 is divided into four sub-sections, which

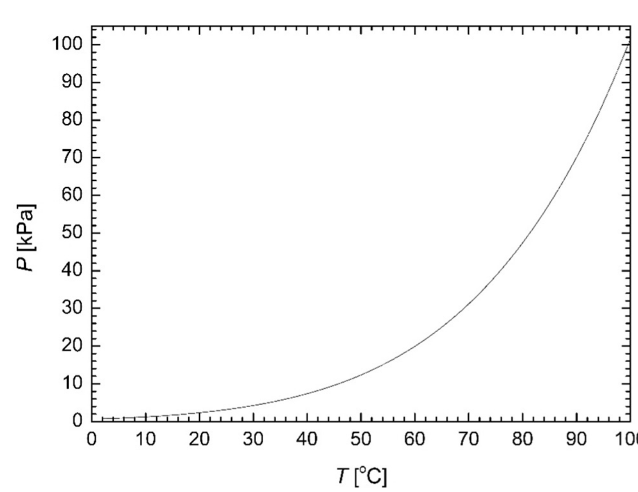

Fig. 1. Saturated vapor pressure of water [17].

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