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Time effect on wetting transition of smart surface and prediction of the wetting transition for critical heat flux in pool boiling

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ABSTRACT

A smart surface that is a TiO_2-coated surface (TCS) is a hydrophobic surface initially, but becomes a hydrophilic surface when heated. Therefore, such a surface can be used to enhance both boiling heat transfer (BHT) and critical heat flux (CHF) in pool boiling. In the present study, the time effect of the wetting transition of TCS was focused on. The CHF on TCS was enhanced more when the holding time of the heat flux in high-temperature regime was increased. By observing changes in contact angles on TCS through heat treatment in air, it was found that the wetting transition was affected not only by the temperature, but also by the time. Thus, a variation of the receding contact angle was correlated in the form of an exponential function. The suggested empirical correlation includes temperature and time, and it describes the transition of the receding contact angle. The correlation was also used to predict the CHF on TCS in pool boiling. As a result, CHFs on TCS could be explained using the correlation.

1. Introduction

Boiling is an efficient heat transfer method because it uses latent heat. For this reason, many applications have used the boiling system. However, the critical heat flux (CHF) imposes a limitation on the practically available boiling regime. When CHF is reached, a vapor blanket forms on the heated surface, resulting in an interruption in phase changes and a deterioration in the boiling heat transfer (BHT). Then, the heating substrate melts due to the reduced heat removal capacity.

In this respect, for safe and efficient heat transfer systems, it is important to improve CHF and BHT. As technology has advanced, many techniques have been suggested to improve the CHF and BHT. To be specific, the surface modification technique, due to its applicability into real systems, e.g., machining, chemical etching, coating of thin layers, and deposition of particles, is one of the most promising methods for the improvement of boiling performance. Furthermore, the effect of nanoparticles in pool boiling has been reported on substantially since the advent of nanofluids and their applications [1–9].

Bang et al. [5] investigated the effect of alumina (Al_2O_3) nanofluid on the pool boiling characteristics. The authors prepared alumina nanofluids that had different volume concentrations. In pool boiling, the nanofluids enhanced the CHF, but reduced the BHT. In addition, the higher the concentration of the nanofluid, the lower the BHT. Kim et al. [6] used alumina, zirconia (ZrO_2), and silica (SiO_2) nanofluids to examine the effect of nanoparticles on the pool boiling characteristics. When the authors fixed the volume concentration at 0.01%, the CHF was enhanced for all the nanofluids. It was believed that the improved wettability via nanoparticle deposition contributed to the enhancement of CHF. However, the nanofluids lowered the BHT. Kim et al. [7] utilized alumina and titania (TiO_2), and Stutz et al. [8] adopted iron oxide (Fe_2O_3) nanofluids for the enhancement of CHF in pool boiling. In their studies [7,8], they also agreed that the improved wettability due to the nanoparticle deposition was the main cause of the enhancement of CHF.

The previous studies [6–8] showed that the wettability had an important role in enhancing CHF, regardless of the nanoparticle material. In this respect, different surface modifications were suggested with a focus on the wettability. Ahn et al. [10] fabricated nano-micro structures on zircaloy-4 using an anodic oxidation. The authors controlled the anodization time of zircaloy-4 so that the static contact angle on the surface decreased from 49.3 to 0°, while the modified surface enhanced the CHF by 90%. Chu et al. [11] fabricated hierarchical surfaces by depositing nanoparticles on micropillar posts. In pool boiling, the hierarchical surface showed a CHF enhancement of 200% in comparison to that of a

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Nomenclature

a	coefficient
A	constant
b	coefficient
B	constant
C	experimental constant
h_{lv}	latent heat (kJ/kg)
k	rate constant (/min)
q''	heat flux (kW/m^2)
R	constant
SCS	SiO$_2$-coated surface
t	time (min)
T	temperature (K)
T^*	normalized temperature, T (°C)/200 °C
T_s	surface temperature (K)
T_∞	ambient temperature (K)
TCS	TiO$_2$-coated surface

Greek symbols

ϕ	orientation of heating surface (°)
θ	static contact angle (°)
θ^*	normalized receding contact angle, $\theta_r/90^\circ$
θ_0	contact angle constant (°)
θ_r	receding contact angle (°)
ρ_v	vapor density (kg/m^3)
σ	surface tension (N/m) or Stefan-Boltzmann constant (5.67×10^{-8} W/m^2 K^4)

Subscripts

a	the coefficient of a
b	the coefficient of b
l	liquid
n	coefficient indication
v	vapor
lv	phase change from liquid to vapor
CHF	CHF

smooth surface. In their study, the higher the roughness, the higher the CHF. However, BHT decreased as the roughness increased. The researchers believed that the thermal resistance of the hierarchical surfaces was the reason for the deterioration of BHT.

Even though nanoparticle deposition enhanced the CHF due to the improved wettability, some studies [5–8,11] have identified a deterioration of BHT. However, other studies [9,12] have overcome the deterioration of BHT. Kim et al. [9] used microelectromechanical systems (MEMS) to manufacture nanostructures, microstructures, and nano-micro combined structures on silicon substrates. In pool boiling, the nano-micro structured surface showed a CHF enhanced by more than 107%, which was contributed to the increased wettability. In particular, the structures improved not only the CHF, but also the BHT. Betz et al. [12] focused on wetting control without structural changes. The authors fabricated mixed wetting surfaces: one type had hydrophobic hexagon patterns on a hydrophilic surface, while another surface had hydrophilic hexagon patterns on a hydrophobic surface. The mixed wetting surface improved the BHT and CHF by 100% and 65%, respectively, in comparison to those for a plain surface.

As reported in previous studies [9,12], enhancement of both BHT and CHF requires intricate technology because there is a trade-off between BHT and CHF when the wettability is modulated. In studies [13,14], nanometrically smooth hydrophobic surfaces showed better BHT than did hydrophilic surfaces in pool boiling; hydrophobic surfaces have been found to be advantageous for high BHT, but are known to have low CHF. On the other hand, hydrophilic surfaces have showed a BHT lower than that of hydrophobic surfaces, but can have a higher CHF.

In this regard, Kim et al. [15] suggested a smart surface, which is a TiO$_2$-coated surface (TCS), to enhance both BHT and CHF in pool boiling. The authors noted that the properties of hydrophobicity and hydrophilicity have different effects on the boiling performance. So, they focused on the wetting transition of TCS. In several studies [16–18], TiO$_2$ was found to have a wetting transition that is dependent on the temperature. TiO$_2$ initially shows a hydrophobic characteristic, but it becomes hydrophilic when heated. Kim et al. [15] conducted pool boiling experiments using TCS and observed that TCS increased not only the BHT, but also the CHF. They reported that this result was contributed to the wetting transition of TCS. In addition, it was suggested that time was an important factor in the change of wettability, and could lead to an additional enhancement of CHF.

The present study focused on the time effect of the wetting transition of TCS. Through heat treatment with changes in the treatment temperature and time, the variation of the receding contact angle was examined, and an empirical correlation was provided. In addition, the empirical correlation was combined with Kandlikar's correlation [19] to predict the CHF trend on TCS.

2. Experiments

2.1. Surface fabrication

A 500 μm thick silicon wafer was used as a base substrate. Since the silicon surface had a ~1 nm roughness, we considered that the roughness effect could be excluded based on Hsu's theory [20]. For the heating of the substrate, a heating element was fabricated on the back of the substrate, as shown in Fig. 1. On one side, an SiO$_2$ thin film with a thickness of 500 nm was deposited for electrical insulation. A photoresist (GXR601, Electronic Materials) was coated on the insulated silicon wafer using a spin coater (ATIS, Midas System) at 3000 rpm. Then, the coated photoresist (PR) was exposed to ultraviolet (UV) light through a patterned mask using a mask aligner (MA6, Suss Microtec). The exposed wafer was immersed in tetramethylammonium hydroxide (TMAH) solution, and so a reversed pattern of the PR was made on the wafer. On this surface, using an electron beam evaporator (E-beam), a platinum (Pt) layer with a thickness of 120 nm was deposited. When the Pt coated wafer was immersed in acetone, only the Pt pattern remained after the residual PR layer was removed. As a result, a heating element that has an effective heating area of 10 × 10 mm was fabricated.

On the other side of the substrate, thin films for boiling surfaces were deposited. A 500 nm-thick SiO$_2$ thin film was deposited on the heating surface as a reference surface; a 200 nm-thick TiO$_2$ thin film was deposited to investigate the wetting transition. A TiO$_2$ layer was deposited using radio frequency sputtering (RF sputtering) at room temperature conditions (~25 °C).

2.2. Experimental facilities

For the investigation of CHF on TCS, pool boiling facilities were constructed. The main pool was made of stainless steel pipe (304 L) that could hold 12 L of deionized (DI) water as a working fluid. In