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Smart surface in flow boiling: Spontaneous change of wettability

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ABSTRACT

We examined the heat transfer coefficients (HTC) and critical heat fluxes (CHF) in flow boiling on titanium dioxide (TiO_2) and zinc oxide (ZnO) coated surfaces that are suggested as smart surfaces in this study. These surfaces were initially hydrophobic; they induced early onset of nucleate boiling (ONB), and many nucleation sites were observed at the initial stage of boiling compared with the SiO_2 reference surface. As a result, high HTCs were identified on the smart surfaces. Additionally, under high wall superheat conditions, the surfaces became hydrophilic; there was no degradation of CHF by promoting water supply to dry areas. The results were attributed to spontaneous change of wettability of the smart surfaces. We investigated the contact angles of the surfaces after they underwent heat treatment. The contact angles decreased on the smart surfaces as the temperature increased. In conclusion, we postulated that the change in the wettability characteristics was a key factor in explaining the improvement of the HTC without degradation of the CHF, and suggest the smart surfaces.

1. Introduction

The flow boiling is an efficient heat transfer mode, comprising both nucleate boiling and forced convection effects. There are two important factors related to the heat transfer performance of the flow boiling system: the heat transfer coefficient (HTC) and the critical heat flux (CHF). HTC indicates the efficiency, and CHF limits the heat flux available by the boiling heat transfer due to formation of vapor blanket on the heated surface, which induces heat transfer degradation and jump of the surface temperature. For these reasons, to improve the efficiency and safety of a flow boiling system, we focused on the improvement of HTC and CHF.

Wettability has attracted attention because it has significant effects on HTC and CHF. Wettability can be altered by changing the morphology or chemical composition of a surface [1–3]. A surface can be classified as hydrophobic or hydrophilic, according to its wettability. A hydrophilic surface has a positive effect on CHF due to improved liquid supply to the dry areas. On the other hand, the hydrophobic surface gives rise to early onset of nucleate boiling (ONB) and many nucleation sites at low wall superheating temperatures in pool [4–6] or flow boiling [7]. This causes an improved HTC during the initial stage of boiling. Hydrophobic surfaces has been less studied than hydrophilic surfaces as they are likely to induce early CHF due to the premature formation of the vapor blanket. Therefore, surface modifications to enhance the wettability were the direction of study in the field of flow boiling so far. Such modifications include microstructures [7,8], coatings with microparticles [9,10], and coatings with nanoparticles [11–13].

Sommers et al. [7] fabricated micro-structures on an aluminum to examine the flow boiling performance using R-134a for mass fluxes from 100 to 600 $kg \cdot m^{-2} \cdot s^{-1}$. According to their results, the laser-etched micro-grooves exhibited improved HTC compared with flat surfaces. Additionally, a surface with a hydrophobic coating had a higher HTC than the uncoated surface. Their results showed a 90–100% improvement of HTC on the laser-etched surfaces compared with an untreated flat surface. Hydrophobic coatings with laser-etched grooves increased HTC by 20%.

Ahn et al. [8] used anodic oxidation to make micron-scale irregular structures on an inner surface of Zirlo tube. After the Zirlo tube surface was modified, the static contact angle of water changed from 88° to 0°. From results concerning subcooled flow boiling with mass flux of 300–1500 $kg \cdot m^{-2} \cdot s^{-1}$ of deionized (D.I.) water, they concluded that the CHF was enhanced by up to 60% for the micro-structured Zirlo tube. This enhancement was attributed to the improved liquid spreading.

Rainey et al. [9] examined the effect of microporous surfaces on flow boiling in a 12.7 mm × 12.7 mm rectangular channel. FC-72 was used as the working fluid at a subcooling of 4–20 K with velocity 0.5–4 $m \cdot s^{-1}$ at atmospheric pressure. A 10 mm × 10 mm copper heater was coated with aluminum particles of sizes 1–20 μm that form a microporous layer. The microporous coating enhanced CHF

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by up to ~75%, but the enhancement ratio with respect to the plain surface decreased with increasing velocity.

Sarwar and Chang [10] also fabricated porous surface coatings using microparticles. On the porous surfaces, the CHF was observed for inlet subcooling of 75 and 50 °C for mass flux ranging from 100 to 300 $kg{\cdot}m^{-2}{\cdot}s^{-1}$. From the experimental results, they confirmed CHF was enhanced by up to 25% on microporous Al_2O_3-coated surfaces and by 20% on TiO_2-coated surfaces with respect to the smooth surface.

The study by You et al. [14] demonstrating enhanced boiling performance via nanoparticle addition to the fluid, prompted numerous investigations into the use of nanoparticles/nanofluids in the working fluids of boiling system. Kim et al. [11] conducted experiments using Al_2O_3 nanofluids, based on D.I. water at subcooling temperatures of 25 and 50 °C, with mass fluxes from 100 to 300 $kg{\cdot}m^{-2}{\cdot}s^{-1}$. From their results, the CHFs were enhanced by up to 70% when nanofluids were used as the working fluid, regardless of the subcooling level. They attributed the enhancement of the CHF in nanofluids to improved wettability. This occurred due to nanoparticle deposition on the surface during boiling.

Ahn et al. [12] used an Al_2O_3 nanoparticle-deposited surface as a heating surface in flow boiling with velocities ranging 2–4 $m{\cdot}s^{-1}$ with D.I. water. They observed a 32% enhancement in CHF on the nanoparticle-deposited surfaces, as well as a decrease in the HTC; these results were attributed to the improved wettability due to nanoparticle deposition.

Recently, Seo and Bang [13] investigated the heat transfer on nanoparticle-deposited surfaces. Nanoparticle-deposited surfaces were prepared using a quenching process in an Al_2O_3 nanofluid [15]. Subcooled R-123 flow boiling experiments were conducted on the surfaces with the mass fluxes, 1600–2600 $kg{\cdot}m^{-2}{\cdot}s^{-1}$. The CHF was enhanced by up to 16%. CHF enhancement was ascribed to the rewetting process facilitated by capillary effects.

The surface modifications suggest that HTC and CHF can be improved by controlling the wettability using coating with chemicals or changes of the morphology. However, it's hard to enhance both HTC and CHF through surface modification or to improve HTC without degradation of CHF. In this study, we tried to enhance both HTC and CHF using the smart surfaces. Sun et al. [16] reported that the wettability properties of TiO_2 and ZnO surfaces changes as the temperature increases. TiO_2 and ZnO were initially hydrophobic, with contact angles 60° and 120°, respectively. However, after annealing at temperatures above 200 °C, these surfaces became hydrophilic with contact angles approximately 20°. As the annealing temperature approached 250 °C, the contact angles decreased continuously, below 10°. The wettability was also reported to be temperature-dependent by Zheng et al. [17] and Meng et al. [18], most likely due to the dissociative adsorption of water molecules on TiO_2 [16,19,20] or O atoms which lies on ZnO, causing interactions with H_2O molecules [18,21]. The details of the mechanism for the interaction between water and the surface are beyond the scope of this study; thus, they are not covered in detail.

In this study, we propose a concept of the "smart surface" that changes the wettability so that HTC is improved without degradation of CHF through flow experiments with wettability analysis. TiO_2 and ZnO were used as coating materials for the purpose by utilizing the spontaneous change of wettability with the temperature change. In the low heat flux region, bubbles were generated vigorously on TiO_2 and ZnO due to hydrophobicity. In the high heat flux region (high wall temperature region), it was postulated that surfaces became hydrophilic causing compensation of CHF. This promoted water supply to the dry areas and delayed the burn out. This change of wettability was the key characteristic in explaining the boiling performance enhancement induced by TiO_2 and ZnO coatings. This spontaneous change resulted in improved HTC without degradation of CHF.

2. Experimental setup for flow boiling

A flow boiling loop (Fig. 1) was used to investigate flow boiling phenomena on TiO_2 and ZnO. All experiments were conducted at low pressure (170–300 kPa) and with subcooled D.I. water. The

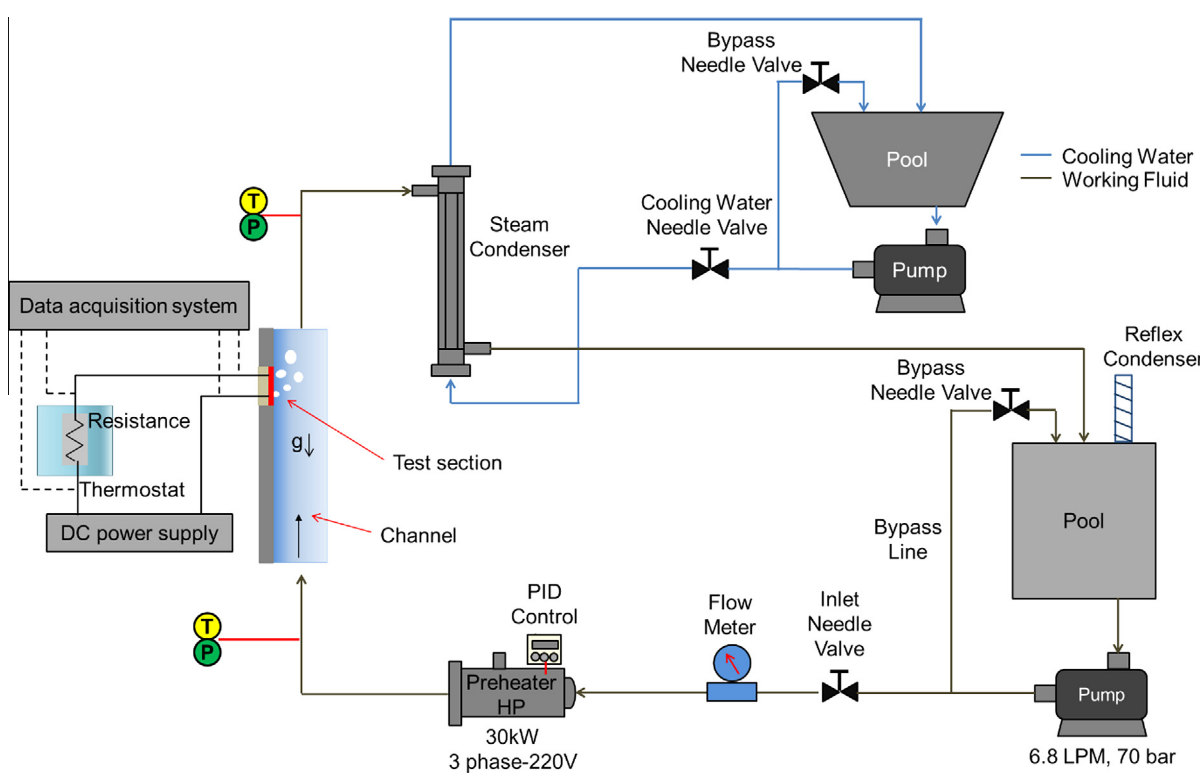

Fig. 1. Flow boiling loop.