



Influence of heated surfaces and fluids on pool boiling heat transfer



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ABSTRACT

The influence of heated surfaces and fluids on pool boiling heat transfer was investigated experimentally. As the test specimen, Plain Surface (PS) and Nano-Structured Surface (NSS) were used. As the test fluid, pure water, an aqueous Lithium Bromide (LiBr) solution, and an aqueous Sodium Dodecyl Sulfate (SDS) solution were tested. Under the saturated water and aqueous LiBr solution conditions, the NSS showed a lower Onset of Nucleate Boiling (ONB) and higher Nucleate Boiling Heat Transfer Coefficient (NBHTC) than the PS. On the other hand, under aqueous SDS boiling conditions, the NBHTC was increased on the PS, but decreased on the NSS, as compared with under pure water boiling conditions. It was found that the interaction and combination between the heated surface and fluid can be an important parameter affecting the boiling heat transfer performance, and both the surface tension and surface wettability (i.e., contact angle) should be taken into account. The change of water contact angle induced by the chemical reaction between the heated surface and fluid was examined and discussed. As the test surface, copper PS, titanium PS, and titanium dioxide NSS were prepared. Then, they were boiled under saturated water and butanol conditions for 8 h, and their water contact angles were compared with the fresh (i.e., pre-boiled) surfaces. The water-boiling process remarkably decreased the water contact angles for all surfaces, as compared with the butanol-boiling process. This implies that the chemical reaction between the heated surfaces and boiling fluids affects the surface wettability, which can strongly influence the pool boiling heat transfer performance.

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1. Introduction

Nucleate Boiling Heat Transfer (NBHT) has been considered an effective way to remove the higher heat flux at a given temperature difference compared with a single phase heat transfer. Among the various active and passive techniques to improve the NBHT, the modification of the surface structure and the use of an aqueous surfactant solution have been widely used [1,2].

In numerous studies and experiments, enhancements of NBHT through adapting micro-scaled surface geometries/structures have been reported [3–8]. A structured surface can provide a number of small cavities on the boiling surfaces, and increase the vapor/gas entrapment and the number of active nucleation sites. These lead to reducing the incipient and nucleate boiling wall superheats and increasing the NBHT [8]. In addition, researches on the

enhancement of NBHT using nano-fluids and Nano-Structured Surfaces (NSSs) [9–14] have been carried out, and reported extensively. Our group has also studied well-defined nano-materials suitable for use in NBHT [15,16]: Vemuri and Kim [15] carried out a brief experimental study on the Nucleate Boiling Heat Transfer Coefficient (NBHTC) of a NSS using commercially-available aluminum oxide with a thickness of 70 μm in a saturated FC-72 dielectric fluid. This study revealed that the incipient wall superheat was reduced by 30% in the input power for the NSS versus the Plain Surface (PS). The enhancement of NSS can be due to increasing both the vapor entrapment volume and the active nucleation site density. Later, Lee et al. [16] performed pool boiling experiments with the vertical columnar NSS fabricated by an anodizing technique. An anodizing technique has been recognized as an efficient way to grow well-ordered oxide nano-structures on a metal surface, which is cost-effective and simple. The incipient wall superheat of pool boiling in NSS was lower than that in PS. The NBHTC of NSS appeared higher than that of PS, particularly at the low heat flux condition.

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Nomenclature

A	surface area (m ²)	ΔT	wall superheat (°C or K)
A_p	projection area (m ²)	V	voltage (V)
A_r	rough surface area (m ²)	<i>Greek letters</i>	
D_c	cavity mouth diameter (m)	θ_A	apparent contact angle (radian or °)
I	current (A)	θ_l	intrinsic contact angle (radian or °)
i_{fg}	latent heat of vaporization (kJ/kg)	ρ_v	vapor density (kg/m ³)
N_a	active nucleation site density (#/m ²)	σ	surface tension (N/m)
q''	heat flux (kW/m ²)	σ_{lv}	interfacial tension of liquid-vapor (N/m)
R	roughness factor (–)	σ_{sl}	interfacial tension of solid-liquid (N/m)
T_{sat}	saturation temperature (°C or K)	σ_{sv}	interfacial tension of solid-vapor (N/m)
T_w	wall temperature (°C or K)		

Another way to enhance the NBHTC is to use a surfactant. A small amount of surfactant to water can dramatically change the boiling phenomena [17–19]. Ammerman and You [17] investigated the boiling enhancement mechanism using a photographic/laser-doppler anemometry measurement technique in saturated water with three different concentrations of an anionic surfactant, Sodium Dodecyl Sulfate (SDS). They concluded that for the heat flux in the fully developed boiling region, the addition of SDS to water increased the convection component and reduced the latent heat component, and that this relative change of heat flux components has an influence on the boiling enhancement. Wasekar and Manglik [18] experimentally studied the NBHT using SDS. By the addition of SDS to water, NBHTC was significantly enhanced, and Onset of Nucleate Boiling (ONB) occurred early, as compared with pure water. They reported that the optimum level of enhancement was observed in the solutions at or near the Critical Micelle Concentration (CMC) of the surfactant, and the dynamic surface tension had an important role in the modification of the bubble dynamics and NBHT. Hetsroni et al. [19] investigated NBHT and bubble dynamics (e.g., bubble nucleation, growth, and departure) under the saturated and subcooled conditions using environmentally acceptable nonionic surfactant solutions. In their study, as the concentration increased, the NBHTC increased in both the saturated and subcooled conditions. They reported that the boiling curve under the saturated condition was definitely different from that under the subcooled condition, and mentioned that this cannot be explained by the ionic nature of the surfactant and the surface tension.

On the other hand, a Lithium Bromide (LiBr) and water (H₂O) solution is widely recommended for use as the working fluid in vapor-absorption air conditioning systems. An absorption type refrigeration system mainly uses H₂O/LiBr as a typical refrigerant/absorbent combination. The investigations on pool boiling heat transfer using the aqueous LiBr solution have been experimentally performed. Varma et al. [20] reported the effect of heater tube diameter and concentration of aqueous LiBr solution (e.g., 0, 30, 50 and 60 wt%) on NBHTC. The NBHTCs were not affected by the heater diameter, but the concentration of LiBr solution was an important determining factor: Increasing the concentration leads to reducing the NBHTCs. Wu et al. [21] checked the performance of NBHT using pure water and 50 wt% LiBr solution with various amounts of n-octanol. They reported that the addition of n-octanol to pure water and concentrated LiBr solution did not significantly enhance the NBHT. Meanwhile, NSS may help improve the performance of a vapor-absorption system. However, none of the experimental researches using the NSS under an aqueous LiBr solution are available.

The objective of the present study is to investigate the influence of the heated surface and fluid on the pool boiling heat transfer. For boiling experiments, as the test specimen, the aluminum

alloy-based PS and sponge-like NSS are prepared and tested. As the test fluid, aqueous LiBr and SDS solutions as well as the pure water are used. Based on the boiling heat transfer measurement and visualization, the influence of the interaction and combination between heated surfaces and fluids on the pool boiling heat transfer is examined. In addition, the changes in Water Contact Angles (WCAs) induced by the chemical reaction of the heat transferred materials (e.g., copper PS, titanium PS, and titanium dioxide NSS) under the saturated water and butanol conditions are reported and discussed.

2. Experimental details

In Fig. 1, a schematic diagram of the experimental set-up for pool boiling is shown. The boiling chamber is composed of a 101.6 mm wide and 254 mm long square stainless steel tube and two Teflon end-plates. The test section is mounted on the side wall of the test chamber using a specialized fitting. A T-type thermocouple is used to measure the temperature of the liquid pool. An auxiliary cartridge heater is installed to provide additional heating during the degassing process. An O-ring is used on the Teflon plates to ensure a good seal. The test chamber is insulated to prevent possible heat transfer from the surrounding area. For boiling visualization, a round glass window is prepared. An AC (Alternating Current) variable transformer is used to supply a controlled amount of power to the cartridge heater. Two high-accuracy digital multi-meters (Agilent 34410 A and Fluke 87 V, respectively) are used to measure the voltage and the current to calculate the applied power. To condense the vapor generated from the boiling chamber, a reflux glass condenser and a constant temperature controller (PolyScience) are installed. All of the temperatures in the experimental set-up are monitored and stored using a data acquisition system (IOtech).

In Fig. 2, the schematic diagram of test section is displayed. As the test section, an aluminum alloy rod (Type 6061, 19.1 mm in diameter and 101.6 mm in length), with a center hole (9.5 mm wide and 99.1 mm long), is used. Four holes, each 2.4 mm in diameter and 70.0 mm in depth, are drilled at the top, middle, and bottom 90° apart along the periphery of the test section. In order to heat the test section, a cartridge heater (diameter of 9.5 mm and a length of 76.2 mm) is tightly inserted into the center hole. T-type thermocouples (Omega) are installed in the small exterior holes to measure the surface temperatures.

Two kinds of test surfaces are prepared by electro-polishing (for PS) and two-step anodizing (for NSS) techniques, respectively: The aluminum alloy specimens are annealed at 400 °C for 4 h and then cooled to room temperature. The heat-treated specimens are electro-polished in perchloric acid and ethanol (1:4 by vol) at 12 V for 5 min at 0 °C. The finished specimens are thoroughly rinsed with

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