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Effect of surface roughness on pool boiling heat transfer of water on hydrophobic surfaces

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ABSTRACT

The effect of surface roughness on the pool boiling of water on hydrophobic surfaces was investigated over the entire boiling regime, from the onset of nucleate boiling to film boiling. The hydrophobic surfaces were fabricated by coating a polytetrafluoroethylene layer on 10×10 mm^2 copper surfaces roughened by various sandpapers. The average roughness of the hydrophobic surfaces ranged from 0.042 to 1.54 μm and the corresponding contact angles varied from 116° to 153°. Boiling heat transfer coefficients (BHTC) for the rough surfaces were initially high, but decreased rapidly as the heat flux increased, whereas the BHTCs for the smooth surfaces slowly increased to reach their maximum values and then decreased. The variation in BHTC was explained in terms of the number of nucleation sites and vapor blanketing on the boiling surface, which were related to both the roughness and contact angle. An empirical critical heat flux (CHF) correlation, which showed a 12.2% mean absolute error with the present data, was proposed. Inclusion of the current CHF data for the hydrophobic region provided a complete understanding of the effect of surface roughness and wettability on the CHF in pool boiling of water.

1. Introduction

Boiling heat transfer has been regarded as one of the most effective cooling technologies for high-performance applications such as avionics, spacecraft, military equipment, and mobile devices. Nucleate boiling is a complex phenomenon because it involves interactions between three phases, namely, solid, liquid, and vapor. Although, rigorous studies have revealed the considerable effects of primary parameters such as pressure, subcooling, and orientation on boiling heat transfer, impact of the surface characteristics of heated surfaces were not clearly elucidated until recently. Currently, interest in surface conditions, for instance, wettability and roughness, has been increasing in response to the development of surface modification techniques via micro/nano fabrication. Various types of microstructures and nanostructures have been fabricated and examined with respect to their boiling heat transfer performance [1–4]. It was clarified that superhydrophilicity, resulting from the existence of nanostructures or a combination of microstructures and nanostructures on the boiling surface, facilitates rewetting of dried vapor patches; thereby, augmenting the critical heat flux (CHF) tremendously by more than double that of the bare surface in water [3,5,6]. However, in contrast with the augmented CHF, the boiling heat transfer coefficient (BHTC) for the superhydrophilic surface decreased relative to that of the normal bare surface, which was ascribed to the diminished number of active nucleation sites owing to flooding of the promising cavities on the boiling surface [7,8]. Kim et al. [9] closely reviewed pool boiling enhancement studies on the micro/nanostructured surfaces formed by various surface modification techniques. They summarized the features of the BHTC enhancement techniques and those of the CHF enhancement techniques, respectively.

Hydrophobic and superhydrophobic surfaces, which are at the opposite extremes of wettability, have emerged in the field of nature-inspired surface modification techniques using nanostructures [10] and are also receiving much attention with regard to boiling heat transfer. In 1969, Hasegawa et al. [11] first experimentally demonstrated the reduction in maximum heat fluxes on ill-wettable heating surfaces or hydrophobic surfaces. A more detailed investigation of the bubble behavior on hydrophobic surfaces was conducted in the recent research studies of Nam et al. [12] and Bourdon et al. [8]. Nam et al. [12] showed, through experimental observation and numerical simulation, that a single bubble on a hydrophobic surface was thrice the size and had 60 times longer cycle time than on a hydrophilic surface. Bourdon et al. [8] obtained a higher BHTC for a hydrophobic surface than a hydrophilic surface at the onset of nucleate boiling (ONB). Other researchers

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Nomenclature

BHTC	boiling heat transfer coefficient
CHF	critical heat flux
h	heat transfer coefficient (W/m^2 K)
h_{fg}	heat of vaporization (J/kg)
ONB	onset of nucleate boiling
P	pressure (Pa)
q''	heat flux (W/m^2)
r	radius of curvature of a bubble (m)
R	radius of cavity mouth (m)
R_a	average roughness (m)
T	temperature (K)
v	specific volume (m^3/kg)
v_{lv}	$v_v - v_l$, specific volume difference (m^3/kg)
Greek symbols	
ΔP	$P_l - P_v$, pressure difference (Pa)
ΔT	$T_w - T_{sat}$, wall superheat (K)
θ	contact angle (°)
σ	surface tension (N/m)
Subscripts	
L	liquid
sat	saturation
v	vapor
w	wall

also reported an increase in BHTC [7,13] and decrease in CHF [13,14] on hydrophobic surfaces. Earlier nucleation on hydrophobic surfaces is well accepted in accordance with the thermodynamic considerations of the bubble nucleation process in a cavity on the heated surface. Based on the understanding of pool boiling on a homogeneous hydrophobic surface, research efforts were directed to study the boiling phenomenon on mixed or heterogeneous surfaces combining hydrophilic and hydrophobic surfaces [13,15–17]. They all reported an increased BHTC for a heated surface containing hydrophobic dots on a hydrophilic background while retaining the CHF to be as high as that on a homogeneous hydrophilic surface. Recently, Jo et al. [18] conducted an elaborate study focusing on the dynamics of a single bubble on mixed surfaces. They demonstrated that the contact angle varied on the hydrophobic dots owing to contact line pinning, and the maximum BHTC was obtained by optimizing the diameter and pitch of the hydrophobic dots on the heterogeneous surface. Lee and Lee [19] also proposed a BHTC and CHF optimization method using a non-uniform distribution of hydrophobic dots on the mixed surface.

State-of-the-art studies on heterogeneous surfaces combining hydrophobic and hydrophilic surfaces have increased our understanding of the wettability effect on boiling heat transfer. However, it does not imply that our understanding of the boiling phenomena on homogeneous hydrophobic surfaces is fully established. There are still various factors that are related to the boiling heat transfer on hydrophobic surfaces, for instance, heater size, inclination, surface porosity, and transition to film boiling. Surface roughness is one of the factors that is known to affect the boiling phenomena. It is regarded as one of the most important surface characteristics along with surface wettability. Although the effects of surface roughness on hydrophilic surfaces have been studied in all aspects extensively [20–22], a study about the effect of surface roughness on boiling for a hydrophobic surface is rare. Kim et al. [22] showed that surface roughness of hydrophilic surfaces with a moderate wettability augmented both the BHTC and CHF considerably, implying that the effect of surface roughness is distinct from that of wettability. O'Hanley et al. [21] also emphasized the necessity of a separate investigation for examining the effects of surface wettability and surface roughness on boiling heat transfer. Li and Huang [23] included the effect of surface roughness into their CHF prediction model by formulating the amount of the capillary induced liquid supply using the geometric size parameters and the roughness parameter. In other studies, where surface roughness was utilized to generate superhydrophilic surfaces, it was found to be highly correlated with wettability, and the roughness parameter was directly correlated to the augmentation of the CHF [2,3]. However, it is not yet certain how surface roughness interacts with the wettability of a hydrophobic surface, which is actually the purpose of the present study.

The present study is aimed to investigate the effect of surface roughness on the pool boiling of water over homogeneous hydrophobic surfaces. The boiling phenomena over the entire boiling regime, from the ONB to film boiling, are examined. These results are compared against prior findings to clarify the difference in the boiling behavior on hydrophobic surfaces versus hydrophilic surfaces.

2. Experimental setup

Pool boiling tests were performed using the boiling chamber illustrated in Fig. 1. The boiling chamber was made of aluminum and had an internal volume was 150 × 120 × 170 mm^3. Pyrex glass viewports were installed at the front and rear sides for visual observation. Two 400-W-cartridge heaters were used to heat the water up to the saturation temperature and eliminate any non-condensable gas in the water via degassing. A 200-W silicone-rubber heater was attached to each short side to maintain the water pool in the saturation state during testing. The internal pressure was measured with a pressure transducer, and a type-T thermocouple was placed in the water to measure the liquid temperature. A reflux coil condenser was connected to the top of the chamber and employed to condense the vapor generated in the chamber and return it to the pool.

Pool boiling tests were performed using the following procedure. Approximately 2 L distilled water was filled into the chamber, and then a fabricated heater assembly was immersed in the water pool. The distilled water was heated up to the saturation temperature at atmospheric pressure and maintained for approximately 1 h to remove non-condensable gases from the chamber. All heaters were turned on during the degassing process. After degassing, the cartridge heaters were turned off, but the silicone rubber heaters were kept on to maintain the water temperature in the saturation state. A DC power supply (Agilent N5771A) supplied electric current to the heater and all relevant data including heater and water temperatures, internal pressure, voltage, and current were acquired through the data acquisition unit (Agilent 34980A). Once the heater temperature reached a steady-state, electric power from the power supply was increased to the next level with an increment of 5 kW/m^2 (2.5 kW/m^2 in case of the roughest surface for sufficient data points). CHF was declared when the heater temperature abruptly increased by more than 20 K compared with the previous steady-state value, and the heater power was automatically terminated. Data acquisition and power control were executed by the National Instrument Labview program.