International Journal of Heat and Mass Transfer 93 (2016) 554–565

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Single bubble dynamics on hydrophobic–hydrophilic mixed surfaces

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ARTICLE INFO

Article history:
Received 18 May 2015
Received in revised form 8 September 2015
Accepted 9 September 2015

Keywords:
Pool boiling heat transfer
Wettability
Interface dynamics
Surface heterogeneity
Surface modification

ABSTRACT

Single bubble dynamics of distilled water were experimentally investigated on hydrophobic–hydrophilic mixed surfaces with hydrophobic dot diameters ranging from 50 μm to 6 mm. The heterogeneity of surface wettability could affect interfacial dynamics and cause the pinning phenomenon of the bubble interface, a contact angle transition, a 'stick–slip' behavior, and the interface necking during bubble growth. The triple line of a bubble initiated from a hydrophobic dot was pinned at its edge where a singularity of the surface wettability occurs. During this contact line pinning, the contact angle of bubble interface decreased. When the contact angle decreased to equal the receding contact angle of a bare hydrophilic surface, the triple line moved outward rapidly; this is called 'slip' behavior. After such process, the nucleated bubble vertically elongated and subsequently departed from the surface. The contact angle transition during the pinning and departing behavior was described by considering the capillary length of the bubble determined by the vertical deformation of bubbles. Using the bubble dynamics on the heterogeneously patterned surface with compactly arranged 50 μm dots, boiling heat transfer coefficient enhanced to 2.1 times that in the bare hydrophilic surface.

1. Introduction

Nucleate pool boiling with bubble dynamics is widely used in various industrial fields such as micro fluids [1,2], electronic [3] and power plant cooling systems [4] because it transfers heat with the latent heat of evaporation better than does single phase heat transfer with sensible heat; therefore predicting and describing bubble dynamics during boiling are essential for optimizing the heat transfer efficiency of a system. Methods to predict bubble departure diameter from a heating surface consider the balance between buoyancy and surface tension [5] and the thickness of the thermal boundary layer [6]. The thermal boundary layer has an important influence on the activity of the surface cavity that could potentially be activated and generate bubbles with trapped vapors on surface micro-defects or micro-cavities [7,8]. A general relation for bubble growth rates in a uniformly superheated liquid [9] is valid in inertia-controlled and heat-diffusion-controlled growth.

The effect of surface characteristics on bubble dynamics has also been investigated. In particular, the surface wettability has dominant effects on the dynamics of the vapor–liquid interface [10]. Son et al. [11] conducted a numerical simulation of a growing and departing bubble on a horizontal surface by including the disjoining pressure effect to account for heat transfer through a liquid microlayer. They quantified the effect of the static contact angle using the level set method to capture the vapor–liquid interface. As a consequence of that, a larger departing bubble was predicted on a surface with a higher contact angle. Abarajith and Dhir [12] also used numerical simulations with contact angles to determine the effect of wettability on bubble departure and growth. In the numerical calculation, the contact angle was assumed to be constant throughout the bubble growth and departure processes. Consequently, the size of the departing bubble and its time to departure both increased with contact angle. Takata et al. [13,14] conducted pool boiling experiments on superhydrophilic and superhydrophobic surfaces and visualized generation of large bubbles at very low superheats on the superhydrophobic surface. Mukherjee and Kandlikar [15] simulated the cyclic growth and departure of bubbles using both a static contact angle model and dynamic contact angle model, and compared the effect of the dynamic contact angle model on bubble dynamics and vapor volume with results obtained with the static contact angle model. Phan et al. [16] studied pool boiling on surfaces that had been wettability-controlled using nanocoatings, and proposed a method to predict departure of a bubble from a hydrophilic surface. Nam et al. [17,18] reported a detailed study of single bubble nucleation, growth and departure dynamics on a hydrophobic and a superhydrophilic surface. The departing bubble diameter was almost three times larger and the growth period 60

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.09.031
0017-9310/

times longer on the hydrophobic surface than on the hydrophilic surface. They also observed the bubble necking phenomenon on the hydrophobic surface. Jo et al. [19] performed pool boiling experiments on fabricated nano/microstructured surfaces used as heating surfaces, employing identical nanostructures with two different wettabilities: hydrophilic and hydrophobic.

However, the capacity of the homogeneous wetting characteristic to enhance boiling is limited. High critical heat flux (CHF) is usually obtained with a hydrophilic surface, but the boiling heat transfer coefficient (BHTC) decreases on a hydrophilic surface compared to a hydrophobic surface. Liaw and Dhir [20] observed that CHF at an equilibrium contact angle of 107° was about 50% of that predicted from the hydrodynamic theory. Based on that, Kandlikar [21] considered the effect of surface wettability on CHF by including the receding contact angle of the heating surface, and demonstrate that CHF decreased as receding contact angle increased. When the receding contact angle was <60°, the variation of CHF resulted by the change of 10° in receding contact angle was less than 5–7%, but the CHF value decreased dramatically as the receding contact angle increased beyond 60°. Jo et al. [19] reported 4.4 times higher CHF on a bare hydrophilic oxidized silicon surface than on a Teflon-coated hydrophobic surface. However, the BHTC of the hydrophilic surface was just ~58% of the BHTC of the hydrophobic surface when heat flux was low ($q'' = 58.5\ \mathrm{kW/m^2}$).

Use of a mixed hydrophobic–hydrophilic surface to achieve the best boiling aspects of both types of surface was first suggested from 50 years ago [22], but surface-modification techniques were not sufficiently developed to attain an optimized surface having high CHF and high BHTC. More recently, precise modification of heterogeneous wetting surfaces has achieved remarkable enhancement of BHTC in a given heat flux regime [23,24]. Betz et al. [23] reported that the CHF and BHTC of the flat surfaces that combined hydrophilic and hydrophobic patterns were 65% and 100% higher than a hydrophilic surface, respectively. Jo et al. [24] demonstrated that 100 μm hydrophobic dots patterned on a hydrophilic surface could achieve 1.8 times higher BHTC than a hydrophilic surface without degrading CHF. To sustain high CHF of a hydrophilic surface, the hydrophobic patterned surface should be fabricated with small area ratio of hydrophobic dots to heating surface [25].

Even though the previous studies showed enhanced boiling on hydrophobic–hydrophilic mixed surface, the mechanism of this enhancement is not understood. In this study, to clarify this mechanism, we investigated single bubble dynamics of distilled water on several kinds of hydrophobic–hydrophilic mixed surfaces. This systematic experimental study of single bubble dynamics on surfaces with patterned wettability is expected to help understand the bubble dynamics and of the effect of spatially-variable wetting surface characteristics on two-phase flow systems.

2. Experimental setup and sample preparation

Single bubble experiments were conducted on hydrophilic–hydrophobic mixed surfaces under the atmospheric condition with the liquid being in a saturation state. Distilled water was used as a working fluid. The main part of the experimental apparatus (Fig. 1) consists of a test sample holder made of polyetheretherketone, an octagonal aluminum cylinder pool, a lid with an immersion heater controlled by a Proportional Integral-Derivative controller, and a reflux condenser. A high-speed camera (Integrated Design Tools, Inc., Y7) was installed to capture images of bubble dynamics. Before conducting main experiments, distilled water was boiled at the saturation temperature for two hours to remove dissolved gas in working fluid.

A silicon wafer was used as a heating substrate. A thin-film heater was embedded in one side of the wafer, and micro-electromechanical system (MEMS) techniques were used to fabricate an array of Teflon dots on the other side of the heating surface (Fig. 2(a)). The sample size of 25 × 20 mm was used. For the thin-film heater, an E-beam evaporator (CENTROTHERM, E1200) was used to deposit Ti (20 nm) as an adhesion layer and Pt (120 nm) as a heating element. The Pt deposited layer has H-shape that consists of two parts for the actual heating and electrode. The electrode part of specimen was directly connected with wires by lead soldering to allow Joule heating as shown in Fig. 2 (a). The actual heating part was rectangular (15 × 10 mm).

The wall temperature was determined from the measured resistance of the heater and an empirically-calibrated correlation between resistance and wall temperature for each sample. The error of data acquisition system (Agilent, 34970A) on the resistance measurement was 0.21 Ω. The calibrated correlations for each sample (Fig. 2(d)) were obtained by measuring the electric resistances of the thin-film heater at constant temperatures from 100 to 150 °C, which were maintained by a convection oven (JEIO TECH, OF-02GW). The average heat flux of the heating area was calculated from the measured heater voltage and current.

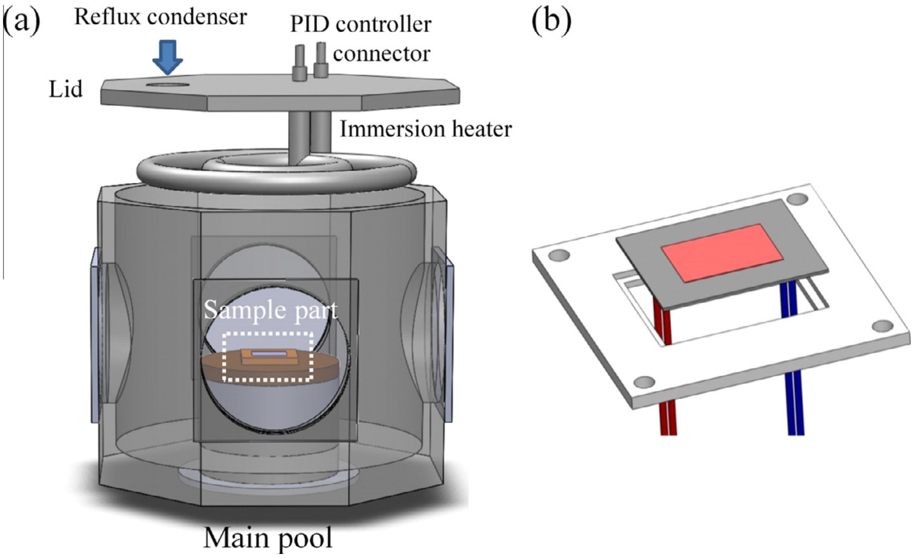

Fig. 1. Schematics of (a) pool boiling facility and (b) sample part.