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Bubble nucleation characteristics in pool boiling of a wetting liquid on smooth and rough surfaces

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ABSTRACT

Quantitative measurements are obtained from high-speed visualizations of pool boiling at atmospheric pressure from smooth and roughened surfaces, using a perfluorinated hydrocarbon (FC-77) as the working fluid. The boiling surfaces are fabricated from aluminum and prepared by mechanical polishing in the case of the smooth surface, and by electrical discharge machining (EDM) in the case of the roughened surface. The roughness values (R_a) are 0.03 and 5.89 μm for the polished and roughened surfaces, respectively. The bubble diameter at departure, bubble departure frequency, active nucleation site density, and bubble terminal velocity are measured from the monochrome movies, which have been recorded at 8000 frames per second with a digital CCD camera and magnifying lens. Results are compared to predictions from existing models of bubble nucleation behavior in the literature. Wall superheat, heat flux, and heat transfer coefficient are also reported.

1. Introduction

Bubble dynamics in pool boiling have been extensively studied since Lord Rayleigh (1917) first derived an expression for the inertially controlled growth or collapse of vapor bubbles, motivated in part by the sound produced inside a boiling tea kettle. The motivation for successive studies has been the formulation of predictive models for heat transfer in cooling systems for nuclear reactors, refrigeration cycles, and electronics. Roughened or otherwise enhanced surfaces are present in many commercial boiling devices, because of the high active nucleation site densities and consequent increase in boiling heat transfer coefficient they produce. The purpose of the present study is to build upon a previous investigation (Jones et al., 2009), in which pool boiling heat transfer from aluminum surfaces with widely varying R_a values was studied with two fluids, water and FC-77, having significantly different wetting characteristics. The experimental results of Jones et al. (2009) were compared to several heat transfer correlations that incorporate surface roughness effects. For the present work, high-speed visualizations of FC-77 boiling from two of the surfaces were obtained so that the bubble nucleation phenomena could be experimentally characterized in detail.

Four physical mechanisms have been suggested for heat transfer occurring during saturated nucleate boiling: microlayer evaporation (Hsu and Graham, 1961; Hendricks and Sharp, 1964), reflooding transient conduction (Forster and Greif, 1959; Mikic and Rohsenow, 1969b), natural convection (Zuber, 1963; Han and Griffith, 1965), and microconvection (Rohsenow, 1952; Forster and Zuber, 1955; Tien, 1962; Kolev, 1995). Later models (Van Stralen, 1970; Judd and Hwang, 1976; Benjamin and Balakrishnan, 1996), and most recently (Moghaddam and Kiger, 2009) have considered more than one of these mechanisms and obtained a good match with particular sets of data included in the validation.

The following bubble nucleation quantities are usually considered in matching model predictions to experimental observations:

1. Average bubble departure diameter, D_d.
2. Average bubble departure frequency, f_d.
3. Average active nucleation site density, N''_A.

In some instances, the bubble terminal rise velocity $v_{b,term}$ has also been considered in the comparisons. In the present study, these four quantities are measured from high-speed movies of saturated pool boiling of FC-77 from two aluminum surfaces of different roughness at four different heat fluxes to generate a detailed database of experimental results.

Much of the literature has concentrated on boiling from either smooth surfaces or those with geometrically idealized cavities such as v-shaped grooves, conical pits, or reentrant cavities. Consequently bubble nucleation characteristics have not been the subject of many detailed studies for surfaces with more naturally and randomly occurring roughness structures, especially where high nucleation site densities occur. In many previous studies using direct measurements from high-speed movie images, such as those of Wang and Dhir (1993a,b), Pinto et al. (1996), Lee

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et al. (2003), and Kim et al. (2006) the bubbles have been relatively isolated from one another. This type of behavior is observed in less wetting fluids, fluids on smooth surfaces, or at low heat fluxes. In other studies, such as those of Abarajith et al. (2004) and Zhang and Shoji (2003), only groups of two to five interacting bubble sites, isolated from other sites on the surface by design, were observed or simulated for the sake of simplicity and to model the specific types of bubble interactions which might occur on the surface. Bubble nucleation interactions may also occur due to thermal diffusion in a conductive substrate, as shown by Chekanov (1977) and Sultan and Judd (1983), although these authors concluded opposite effects. Chekanov found that nucleation at neighboring sites were suppressed by a dominant site, while Sultan and Judd showed that bubble nucleation at one site could produce a wave of high temperature that augmented nucleation at neighboring sites.

Several previous studies have investigated the effect of surface roughness on pool boiling heat transfer. Recently, Kotthoff and Gorenflo (2009) studied the effects of surface roughness and tube diameter on nucleation site density and heat transfer coefficient in pool boiling of various refrigerants and organic liquids from copper tubes. They confirmed previous findings (Gorenflo et al., 2004) that active site densities integrated over time are higher than those apparent over only a few ebullition periods. Together with the surface analysis described by Luke (2009), they concluded that surface roughness descriptions based upon height parameters cannot be used to accurately predict the influence of surface roughness on boiling heat transfer. The works of Luke et al. (Luke et al., 2000; Luke, 2003, 2009) and an earlier study by Bier et al. (1979) calculated cavity sizes from profilometer scan data to predict potential nucleation site size distributions for their surfaces. These and similar studies have linked the surface roughness effect to nucleation site density alone without considering bubble dynamics in detail.

Other studies have shown that surface roughness may affect both static and dynamic contact angles, and have linked this effect to various aspects of bubble nucleation and boiling heat transfer. The early correlation of Fritz (1935), based on a static force balance, relates bubble departure diameter to be in direct proportion to the apparent contact angle. Cornwell (1982) produced a geometric argument for differing values of advancing and receding contact angles on rough surfaces. Tong et al. (1990) summarized the measured values of static contact angle reported in the literature for highly wetting liquids on a variety of surfaces, and then explored the effects of contact angle on boiling incipience. Hong et al. (1994) observed a decrease in static contact angles of water, refrigerants, and alcohols on metal surfaces of increasing roughness and/or degree of oxidation. Bernardin et al. (1997) summarized different definitions for contact angle and tabulated values of advancing contact angle for water on metals with different surface preparation methods, showing the wide range of reported values. Kandlikar and Steinke (2001) examined the effects of copper and stainless steel surface roughness on static, advancing, and receding contact angles of water droplets. They found that values for all three types of contact angle decreased with surface roughness for stainless steel, but first decreased, then increased with increasing surface roughness for copper. Hibiki and Ishii (2003) correlated active nucleation site density with static contact angle, obtaining very good agreement with their model for a wide variety of liquids and test conditions. Lorenz et al. (1974), and Qi and Klausner (2005) demonstrated geometric arguments showing that cavity size and shape, static, and dynamic contact angle can affect the filling and/or vapor-trapping capabilities of nucleation sites. Hazi and Markus (2009) showed through Lattice-Boltzmann simulations that bubble departure frequency, but not the bubble departure diameter, in pool boiling of a water-like fluid was greatly changed by varying the static contact angle parameter. Despite a large amount of data in the literature on the subject, reasons for these contact angle behaviors are still elusive, and a number of authors (Kandlikar and Steinke, 2002; Hibiki and Ishii, 2003) have recommended further study of surface roughness and fluid wetting effects.

In the present study, which expands on preliminary results presented by McHale and Garimella (2008), one smooth surface and one very rough surface producing a high active nucleation site density were included in the testing. In addition, the heat flux was varied over a wide range, approaching the critical heat flux. As a result, bubble interactions and mergers occurred frequently and randomly. The effects of surface roughness and wall superheat on the bubble nucleation parameters are explored. Measurements of the dynamic contact angle θ for growing FC-77 bubbles on aluminum are also reported; to the authors' knowledge, such measurements have not been previously reported in the literature.

2. Experimental setup

A schematic diagram of the test setup, which was modified from that used by Jones et al. (2009), is shown in Fig. 1. Each test piece consisted of an aluminum block into which twelve 3.18-mm diameter cartridge heaters were inserted in a distribution (Fig. 1b) that ensured a uniform heat flux at the top of the test surface. Six 0.81-mm diameter thermocouples were positioned in the upper portion of the block, arranged in two horizontal rows separated by a 3.18-mm gap, so that the temperature of the surface T_w could be obtained by extrapolation. Aluminum silicate insulation was

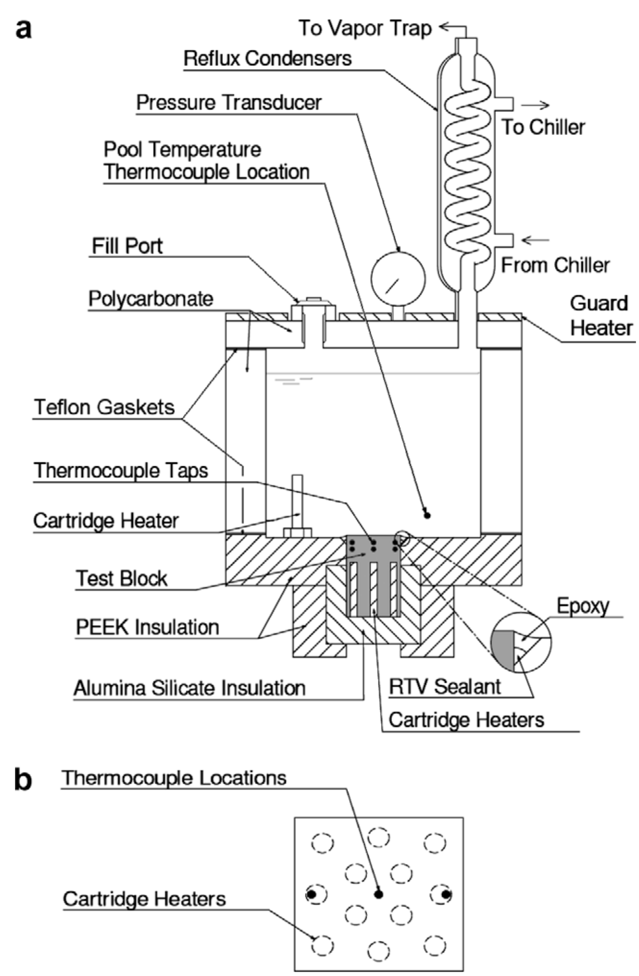

Fig. 1. (a) Schematic diagram of the experimental facility with relevant components indicated and (b) top view of the test block.