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Effect of heater size on ultrasonic enhancement of boiling in water and surfactant solutions

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ABSTRACT

Experiments were performed to study enhancement of heat transfer from the wire of $d = 50$ µm and the tube of $d = 1.5$ mm in subcooled pool boiling by ultrasonic waves. The working fluids are clean water and Alkyl (8-16) Glucoside surfactant solutions of different concentrations and bulk temperature 30 °C. The wire resistance was translated to the temperature, using the calibration data, the temperature of the tube was measured by thermocouple. The differences between effect of ultrasonic field on boiling in water for heaters of $d = 50$ µm and $d = 1.5$ mm may be summarized as follows: for boiling on the wire of $d = 50$ µm in subcooled water, $T_b = 30$ °C, enhancement of heat transfer coefficient due to applied ultrasonic field is about 70% and 20% at heat flux $q = 620$ kW/m^2 and $q = 1350$ kW/m^2, respectively. For boiling in surfactant solutions at the same boiling conditions enhancement of heat transfer coefficient is in the range of 5–10% at heat flux $q = 620$ kW/m^2 and 10–16% at heat flux $q = 1350$ kW/m^2 depending on solution concentration. For boiling on the tube of d= 1.5 mm in subcooled water, T_b= 30 °C, enhancement of heat transfer coefficient due to applied ultrasonic field is about 50% and 45% at heat flux $q = 500$ kW/m^2 and $q = 2500$ kW/m^2, respectively. The same values are obtained for boiling in surfactant solution of concentration $C = 250$ ppm. For the wire of $d = 50$ µm the heat transfer enhancement due to acoustic vibrations in surfactant solutions is not as strong as in water. This fact may be considered as evidence of significant role of relationship between jet flow and ultrasonic field.

Introduction

With new developments in technology and need to more accurately predict heat transfer performance boiling in unconventional environments has been increasingly investigated, especially for micro-scale and microgravity conditions (Sitter et al., 1998). The experiments performed by Sitter et al. (1998) were mounted in a rig designed to fit 0.6 or 2.1 drop tower that employs an air bag as a deceleration mechanism. The average microgravity levels were $5{\cdot}10^{-3}$ and $5{\cdot}10^{-4}$ g. In saturated pool boiling the bubble interface is at saturation temperature and shows no temperature gradients, except for the interface in region of the micro-wedge. According to observation of the surroundings of the heated wall it was suggested by Lu et al. (2006). Pool boiling in terrestrial and microgravity are dependent are dependent on the heater geometry. Thus, a wire heater and a flat plate will affect the departure diameter of the vapor bubbles in different ways. Evaporation and surface tension effects are the basic mechanisms in microgravity. While in terrestrial gravity, buoyancy is the governing mechanism for boiling heat transfer (Sitter et al., 1998).

Subcooled nucleate boiling is characterized by extremely high heat transfer rates. For water systems at near atmospheric pressure the heat fluxes of 10 MW/m^2 and higher can be achieved (Inoue et al., 1998; Fukuda and Sakurai, 2002; Lu et al., 2006). Full utilization of this mode of heat transfer requires reliable knowledge of its limitations such as heated surface geometry and properties of fluid. In subcooled nucleate boiling evaporation and condensation are coupled in a very complex manner as shown by Marek and Straub (2001) for conventional size heaters. If the top of a growing bubble reaches into the subcooled region the vapor starts to condense. The bubble dynamics in subcooled nucleate boiling was studied by Hsu (1962), Robin and Snyder (1970), Takagi et al. (1994), Wu et al. (1999) and Lu and Peng (2008). A flow induced by surface tension gradients is termed Marangoni convection; consequently Marangoni flows may be generated by gradients in either temperature or chemical concentration at the interface. For most fluids the temperature gradient of surface tension $d\sigma/dT$ is negative, i.e. regions of higher temperature exhibit a reduced surface tension.

For very small heaters the ratio of buoyant forces to surface tension forces becomes small and the equilibrium radius of the bubble depends on the heater size. It takes place as the ratio of $R' = r[g(\rho_L - \rho_G)/\sigma]^{0.5} < 0.15$, (Bakhru and Lienhard, 1972) where R' is the dimensionless characteristic of the heater, r is the characteristic

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dimension, usually used to denote the radius of a cylindrical wire, g is the acceleration due to gravity, ρ_L and ρ_G are the saturated liquid and vapor densities, respectively, σ is the surface tension between saturated liquid and its vapor. After boiling inception the bubbles grow on the wire until they are large enough. The bubbles generated on the heated wire are discrete due to influence of subcooled liquid and depart from the wire keeping distinct size called the *detachment* radius. At given experimental conditions high motion pictures were used to calculate the *detachment* radius of a boiling vapor bubbles (Hetsroni et al., 2014).

With the advancement of micro-scale technologies researches have been making both experimental findings and computational predictions that shed more lights towards effect of heater size on nucleate boiling phenomena. The micro-heater array system was first adopted by Rule and Kim (1999) for boiling heat transfer study on micro-heaters. The system featured micro-heaters with a size of 0.27 × 0.27 mm. In the present study we also assign the heaters of size ≤ 0.27 mm as micro-scale heaters. Wang et al. (2004, 2005) and Hetsroni et al. (2014) observed nucleation jet and bubble-top jet flow in a sequence of subcooled boiling experiments on small wires. In general, the bubble jet flow phenomena can significantly enhance the heat and mass transport between the bubble and bulk liquid, and were considered as important complements to nucleate boiling heat transfer. As noted in many investigations (Marek and Straub, 2001; Lu and Peng, 2007), Marangoni flow driven by interfacial tension gradient was expected to play a principal role in bubble jet flow phenomena. The bubble jet phenomena and associated Marangoni flow was investigated during boiling in water. Relatively few studies have considered the effects of surfactant additives on Marangoni convection.

Surfactants are molecules that have an affinity for interfaces. Their presence reduces the surface tension σ; consequently gradients in surfactant concentration C result in surface tension gradients. Boiling with surfactant additives is generally an exceedingly complex process, and it is influenced by a larger set of variables than the phase-change process of pure water. Besides the wall heat flux (or wall excess temperature), heating surface geometry, and bulk concentration of additives, the boiling behavior is also dependent upon interfacial properties, the nature of the additive, its chemistry, foaming etc. The subcooled pool boiling of environmentally acceptable surfactant solutions at various concentrations on macro-scale heaters was studied by Hetsroni et al. (2004). It was found that the subcooled nucleate boiling of surfactants could not be described by a single curve, in contrast to water. They also noted a significant enhancement of the heat transfer and showed drastic change in the bubble structure next to the heated tube wall. For a wide range of common surfactants, surface tension is a monotonically decreasing function of C until a critical concentration is achieved, beyond which σ remains constant. Surfactants thus generate a special class of Marangoni flows. The effect of surfactant concentration on the Marangoni convection around boiling nuclei in aqueous solutions was computationally investigated by Wasekar and Manglik (2003). It was shown in the previous investigations that the Marangoni effect is the most important factor in the heat transfer based on the pumping effect of the jet flow. However, experimental measurements are greatly lack.

Imposing acoustic vibration onto a liquid pool leads to *acoustic streaming*. Cavitation bubbles may be formed both on the wire and in the bulk liquid. The interaction of the bubbles with the ultrasonic field is complicated by local temperature fluctuations of the liquid around the heated wall, Wong, and Chon (1969). The influence of cavitation induced by ultrasound on solid-liquid heat transfer was also investigated in the past by Kim et al. (2004) and Krishnan et al. (2014). The acoustic waves induce acoustic streaming which increases convective heat transfer coefficient. The heat transfer coefficient depends on the *acoustic streaming* resulting from the radial oscillations as well as the rapid erratic motion of the bubbles on the heat transfer surface (Li and Parker, 1967; Vainstein et al., 1995; Uhlenwinkel et al., 2000; Loh et al., 2002; Ro and Loh, 2000). This effect could be very useful in microelectronic packaging. A theoretical study of heat transfer from a vibrating cylinder was done by Davidson (1973). Li and Parker (1967) reported that there was a small reduction in the superheat for saturated boiling of water with ultrasonic waves. The other aspect of ultrasonic waves is the effect on subcooled boiling. Ornanskii and Scherbakov (1959) reported significant increase as subcooling was increased. Park and Bergles (1998) confirmed the effects of ultrasonic waves on boiling heat transfer for an inert, dielectric liquid in subcooled and pool boiling conditions. Their experimental test sections were cylinders of diameters in the range of 1.65 to 2.11 mm, the frequency of ultrasonic waves was 55 kHz and an average intensity of 8 kW/m^2. They observed substantial ultrasonic enhancement when the pool was subcooled, however, accurate data at low heat flux were not obtained due to temperature fluctuations. Iida and Tsudsui (1998) carried out a study of the effect of ultrasonic waves of a frequency of 28 kHz, the magnitude of power supplied was varied from 0 to 41.3 kW/m^2, on natural convection, nucleate boiling and film boiling from a heated 0.2 mm wire to water or ethyl alcohol. No effects were observed in nucleate boiling of water, a small effect was in low heat flux nucleate boiling of ethyl alcohol. An increase was observed of about 20% in the heat flux by applying ultrasonic waves in both liquids in natural convection and film boiling regimes. Bartoli and Baffigi (2011) investigated the influence of ultrasonic waves on heat transfer enhancement. The heater immersed in the water was of 33 mm in diameter and 192 mm in length. The ultrasonic waves were generated at frequencies 37, 38, 39, 40 kHz and varying the heat flux per unit surface in the range was from 120 to 320 kW/m^2. At the best conditions the heat transfer coefficient enhancement was 62%.

Sitter et al. (1998) examined boiling on a wire in the presence of an acoustic field in both terrestrial and microgravity experiments. The experiments performed by Sitter et al. (1998) were mounted in a rig designed to fit 0.6 or 2.1 drop tower that employs an air bag as a deceleration mechanism. The average microgravity levels were $5 \cdot 10^{-3}$ and $5 \cdot 10^{-4}$ g. The acoustic increased the heat transfer coefficient on the wire by directly coupling with the natural oscillations of the vapor bubbles on the wire through the action of the primary Bjerknes force (Bjerknes, 1906). Douglas et al. (2012) studied the effect of an acoustic field on a single vapor bubble on the top side of a horizontal heated surface. The surface consisted of an insulating stainless steel annulus surrounding a thermally conductive 2.4 mm copper pin. A heater was designed to provide a boiling surface that produced a single vapor bubble with a controllable size at a specific location on the surface. The optimal frequency for the removal of vapor bubble of a given diameter depended on the diameter, the liquid density, and surface tension. Effect of subcooling on heat transfer during pool boiling on horizontal heated wires of diameters 0.5–2.0 mm was studied by Inoue et al. (1998). It appears that researches undertaken in the past concerned basic systems, usually with Newtonian fluids, such as heating rods with $R' \geq 0.1$ or walls in a volume subjected to ultrasonic vibrations.

The goal of the present work is to investigate effect of heater size on ultrasonic enhancement of boiling in water and surfactant solutions. An acoustic driver creates an acoustic field in the liquid that can induce oscillations both the vapor bubbles and the heater. The frequency of ultrasonic field was 40 kHz, the *average intensity was* 5 kW/m^2. Two types of heaters were used: the tube of diameter 1.5 mm (R'= 0.3) and the wire of diameter 50 µm (R'= 0.01).The wire was freely fitted between two bars to allow it free oscillations. The coexistence of downward and upward wire motions can bring more violent fluid mixing as compared with taut wire. The present work is an extension of previous study "Ultrasonic enhancement of subcooled pool boiling of freely oscillated wires" (Hetsroni et al., 2014).