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Experimental study of magnetic field effect on bubble lift-off diameter in sub-cooled flow boiling

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A R T I C L E I N F O

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A B S T R A C T

Boiling heat transfer is a process that consist intensive liquid to vapor phase change. Higher heat transfer capacity and lower wall temperatures, which are essential for industrial cooling applications requiring high heat transfer capacities, are vital characteristics of the boiling heat transfer. In spite of tremendous efforts, bubble nucleation and lift-off phenomena in subcooled flow boiling still requires additional studies. Therefore, in this study, the effects of two important parameters including mass flux (85–125 kg/m^2 s) and heat flux (10–40 kW/m^2) on the bubble lift-off diameter in the isolated bubble regime of subcooled flow boiling are studied in the absence and presence of magnetic field caused by quadrupole magnets. The obtained results indicate that by increase of the heat flux and decrease of the mass flux, the bubble lift-off diameter increases. Besides, in the presence of the magnetic field, changes in bubble lift-off diameter follow the same trend. However, it is evident that in the presence of the magnetic field, bubble lift-off diameter decreases 5–10%.

1. Introduction

Boiling heat transfer is a change in phase from liquid to vapor. In cooling industry, specifically in microfluidic devices, boiling is the crucial key to remove high heat fluxes. Flow boiling has a higher heat transfer rate in comparison with pool boiling and other conventional approaches. Moreover, the subcooled flow boiling is also preferred to saturated flow boiling due to its higher heat transfer rate and lower wall temperature. It is worth noting that critical heat flux is a constraint to the boiling heat transfer accompanied by sharp reduction in local boiling heat transfer coefficient and abrupt increase in wall temperature [1].

Numerous methods have been examined so far to increase heat transfer rate and particularly the CHF in forced convection. Despite studies with basic fluids, there are two different approaches to increase heat transfer rate including active and passive approaches. As a passive method, nanoparticles are used for further increase of the heat transfer coefficient. Besides, applying external fields such as magnetic or electrical fields can enhance the heat transfer coefficient as well [2–5].

Although experimental results and numerical simulations [6–8] complement each other, there still is a demand for experimental data and precise knowledge of bubble dynamics, in particular, bubble nucleation site density and bubble departure or lift-off diameter in order to comprehend the elaborate evolution of nucleate boiling. Therefore, a high-speed video camera is used to capture images of bubbles during their growth to reveal the complex phenomenon of nucleate boiling. Ultimately, due to the sophisticated processes of numerical modeling and stochastic nature of boiling [1], it is crucial to study the nucleate boiling and bubble dynamics experimentally.

More recently, mechanistic models have been developed to account for most of the phenomenon involved in nucleate boiling process. Klausner et al. [6] developed a mechanistic model based on the force balance acting on the bubbles during their growth. They could satisfactorily predict bubble departure diameter for saturated flow boiling of R113. Klausner's model has been used as an original model to predict bubble departure or bubble lift-off diameter. Over the years, the aforementioned model has been modified slightly by other authors to predict their own experimental data. Zeng et al. [9] extended the original model to predict bubble lift-off diameter in pool and flow boiling of R113. Later on, Situ et al. [10] experimentally measured bubble lift-off diameter in sub-cooled flow boiling of water in a vertical channel and verified their data against the modified model. Mass flux range was 500–900 kg/m^2 s, and relative error in predicting bubble lift-off diameter was ± 35.2%. Subsequently, Wu et al. [11] conducted an experiment for horizontal flow boiling of refrigerant R134a. It should be noted that Klausner [6] used Mikic [12] model for bubble growth rate, whereas others employed that of Zuber's [7]. Taking account of condensation on the bubble cap, Yun et al. [13] used a model for a non-

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Nomenclature

G	mass flux
q″	heat flux
D_i	outer diameter of the inner tube
L	heated length
d_b	bubble lift-off diameter
r^*	nucleus critical radius
ΔT_{sat}	wall superheat

uniform temperature field coupled with Ranz and Marshal correlation [14] stated by Zuber [7].

Mechanistic model is important for predicting a bubble lift off and experimental studies are crucial to have a deep insight to phenomena. An enormous amount of experimental data is available in literature regarding bubble departure and lift-off diameter. Unal et al. [15] studied the subcooled boiling of water at high pressure in a steam generator pipe as well as bubble departure diameter. Bibeau et al. [16] investigated bubble growth, detachment diameter and condensation during subcooled boiling of water in a vertical annulus. Thorncraft et al. [17] conducted an experiment in a vertical up-flow and down-flow boiling of refrigerant FC-87 to measure bubble departure and lift-off diameter. The ass flux range was 190–660 kg/m^2 s and they concluded that heat transfer rate in up-flow boiling is much higher. Prodanovic [18] studied bubble behavior for sub-cooled boiling of water in a vertical annulus from inception to collapse. Chen [19] measured bubble departure diameter, active nucleation sites as well as bubble departure frequency for a sub-cooled horizontal flow boiling of refrigerant R-407C in an annular duct. Sugru [20] carried out a complete experiment to measure bubble departure diameter for different orientation angles of a square channel. The range of mass flux used in their experiment was 250–400 kg/m^2 s. They compared their experimental data with the predicted diameters from Klausner [6] and Yun [13] model and stated a relative error of 35.68% ± 24.23% and 16.64% ± 11.66%, respectively.

Moreover, as stated before, applying external electrical or magnetic field can be an alternative to increase heat transfer rate. Fujimura [21] studied surface tension of water–air interface in the presence of magnetic field. They detected an increase in surface tension in the presence of a 10 T magnetic field. Stoian [22] investigated the effect of magnetic field at different orientations with respect to gravity on bubble departure diameter of a nano-fluid. They could reach the state that bubble diameters vary from −16% to +12% in departure by applying a magnetic field.

According to the above information, most of the mechanistic models to predict bubble lift-off and departure diameters have relative error of almost 30–50%. This is due to lack of the terms that consider condensation of bubble while it is in contact with subcooled liquid. Furthermore, velocity profile and many other parameters need a more concise approach for better prediction of bubble diameter. It should be noted that predicting bubble lift-off diameter is not the scope of current study. However, for the non-magnetic flow, a code using the forces acting on a single bubble is written to predict the forces during the bubble growth.

A thorough literature review acknowledges that there is limited research on bubble lift-off diameter in convective boiling, which is more important than departure diameter to the interfacial area transport equation while modeling flow boiling. In addition, there is still little data and information regarding the bubble lift-off diameter in the presence of magnetic field in low mass fluxes for subcooled nucleate boiling. Therefore, the primary objective of this study is to investigate the effect of heat flux and low mass fluxes on the lift-off diameter of bubbles in the isolated bubble regime of subcooled flow boiling. Ultimately, the main novelty of this study is to find out the effects of a non-uniform magnetic field on the bubble lift-off diameter. A range of heat fluxes were chosen to ensure that the subcooled flow boiling occurs in a so called ‘isolated bubbles’ regime, where the interactions between bubbles at adjacent nucleation sites could be neglected.

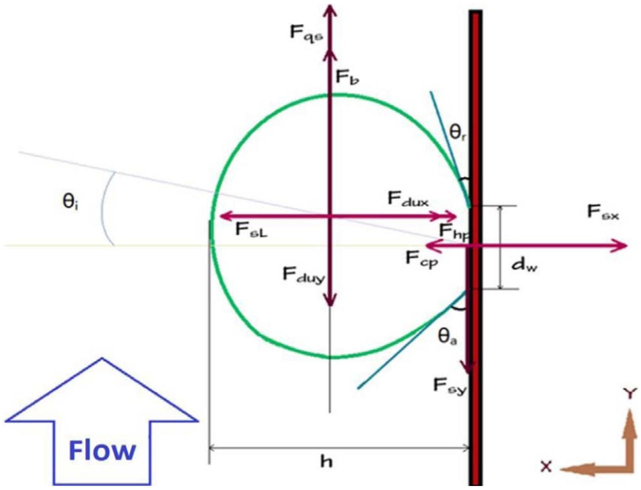

Fig. 1. Schematic diagram of force balance on a single bubble.

2. Force balance on a single bubble at nucleation sites

It is important to know the forces acting on a single bubble in order to determine the bubble lift-off and departure diameter. A bubble in an active nucleation site starts to grow. As soon as the buoyancy force is larger than the other forces in the direction parallel to the flow, the bubble departs from its site and starts to slide along the heated surface until the time that shear lift force exceeds other forces in the direction perpendicular to the flow. That is the point when lift-off takes place. To find out the diameter in which lift-off occurs, it is essential that the balance equations of the forces acting on a bubble to be solved. Fig. 1 shows a schematic diagram of the forces acting on a single bubble in its nucleation site. The force balances in x-direction and y-direction are given by Klausner [6]:

$$\sum \mathrm{F_x} = \mathrm{F_{sx}} + +\mathrm{F_{sl}} + \mathrm{F_{dux}} + \mathrm{F_{hp}} + \mathrm{F_{cp}} = 0 \tag{1}$$

$$\sum \mathrm{F_y} = \mathrm{F_{sy}} + \mathrm{F_{duy}} + \mathrm{F_{qs}} + \mathrm{F_b} = 0 \tag{2}$$

In the above equations, F_s, F_{qs}, $F_s l$, F_{du}, F_b, F_{cp} and F_{hp} are respectively surface tension force, quasi-steady drag force, shear lift force, unsteady drag force, buoyancy force, contact pressure force and hydrodynamic pressure force. Whilst a bubble is in equilibrium, the sum of the forces is zero in both directions. If the forces in the x direction overcome the forces in y direction, lift-off occurs.

2.1. Surface tension force

Equations for surface tension force in x and y directions are [10]:

$$F_{sx} \sim -d_w\sigma\frac{\pi(\theta_a-\theta_r)}{\pi^2-(\theta_a-\theta_r)^2}[\sin\theta_a + \sin\theta_r] \tag{3}$$

$$F_{sy} \sim -d_w\sigma\frac{\pi}{(\theta_a-\theta_r)}[\cos\theta_r-\cos\theta_a] \tag{4}$$

where d_w is bubble contact diameter on the heated wall, σ is surface tension, θ_a advancing contact angle and θ_r receding contact angle. It is worth mentioning that the images taken during current experiment indicate that the advancing and receding contact angles are 85° and 12°, respectively.

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