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Bubble Lift-off Diameter & Frequency in a Vertical Subcooled Boiling Flow

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1. Introduction

Together with an active nucleation site density and a bubble detachment frequency, the bubble detachment diameter determines the evaporative heat flux in commercial CFD codes. Also, an increase of an interfacial area concentration by a wall boiling nucleation, i.e., the boiling source term in an interfacial area transport equation (IATE), is expressed by the above three terms. Several studies were performed to investigate the bubble diameters in the forced convective boiling flows [1-4]. However, the database is still insufficient and the applicability of the suggested models was not thoroughly examined against the existing database. In the present study, the bubble behaviors were captured using a high-speed digital video camera for a forced convective subcooled boiling flow in a vertical annulus. Bubble lift-off diameter and bubble nucleation frequency was quantified by analyzing the captured images. Also, the prediction capability of the models for the bubble lift-off diameter was evaluated against the experimental data of the present work and literature.

2. Experimental Setup and Results

The test facility consists of a transparent vertical annulus test section, a pump, a pre-heater, a condenser and a cooler, a degassing system, measurements instruments, and control and data acquisition system. The vertical annulus test section had a transparent polycarbonate pipe outside a central heater rod. The inner diameter of the polycarbonate (or Lexan) pipe was 31.75 mm and the outer diameter of the heater rod was 9.5 mm. The equivalent hydraulic diameter of the channel was 22.25 mm. The total length of the channel was 1,280 mm. The heating length of the heater rod was 700 mm, the heater had non-heating length of about 485 mm at the upstream of the heating region.

The bubble images from the nucleation to the lift-off and condensation were recorded by HG-100K high speed digital video camera of Redlake Inc. MICRO NIKKOR 105 mm 1:2.8 lens was used. Two Xenon lamps were installed as a back light and a front light, respectively. The basic recording speed and image size of the camera were set to 10,000 frames per second and 192×400 pixels. The distance between neighboring pixels in the recorded image was 12 μm in all cases.

The present experiments were carried out for 15 different test cases combining three mass fluxes of 300, 500, 700 kg/m^2s, two heat fluxes of 140 and 200 kW/m^2, and three subcoolings of about 4, 12, 22 ^oC. The inlet pressure was maintained in the range of 139-152 kPa. The bubble behavior for about nine different nucleation sites was examined in average for each test case. A total of 134 recordings were made, and the bubble lift-off diameter and the bubble nucleation frequency have been being evaluated.

It is generally though that the bubble nucleation activity should increase with the increase of heat flux and the decrease of mass flux and subcooling. However, the bubble lift-off diameter and the bubble nucleation frequency did not showed clear tendency with the change of subcooing, mass flux, and heat flux. When one parameter (diameter of frequency) violated this general thought, the other parameter became more faithful this general thought. For example, (1) the more the frequency increased with the increase of the subcooling, the the more the the lift-off diameter decreased with the increase of the subcooling, (2) when the lift-off diameter increased with the increase of mass flux, the frequency decreased very steeply with the the increase of mass flux, etc. From these observations, it can be concluded that the bubble lift-off diameter and the bubble nucleation frequency has a stochastic feature in nature and they compete with each other for the consumption of the thermal energy from the heated surface.

The bubble nucleation frequency times the square of the bubble lift-off diameter ($f_b*D_{lo}^2$) showed more clear tendency with the change of subcooling, mass flux, and heat flux. In addition, this tendency coincided with the general thought mentioned above. Therefore, $f_b*D_{lo}^2$ could be one promising parameter to explain the bubble nucleation and the bubble lift-off in forced convective subcooled boiling flows. It is worthwhile to mention that Ivey [5] suggested that the bubble nucleation frequency times the square of the bubble departure diameter ($f_b*D_d^2$) was constant for thermodynamic region in pool boiling systems.

In the present study, the database for the bubble lift-off diameter was built by gathering and summarizing the data of Prodanovic et al., Situ et al., and the present work. The prediction capability of Unal's model, Situ et al.'s model, and Prodanovic et al.'s correlation was evaluated against the database. Situ et al.'s model showed good agreement with their data with average error of 35.5% (Fig. 1). But, their model significantly over-predicted the data of Prodanovic et al. and the present work (Fig. 1). As shown in Fig. 2, Unal's model gave reasonable agreement with Prodanovic et al.'s data (average error of 49.1 %), the present data (average error of 33.2 %), but slightly over-predicted Situ et al.'s data (average error of 87.7 %). In the present study, Unal's model was slightly modified by changing the wall superheat correlation with the modified Chen's correlation. As shown in Fig. 3, the modified Unal's model agreed very well with all the data gathered in the present work. The average prediction error was 37.0 %, 27.2 %, and 29.8 % for the data of Prodanovic et al, Situ et al, and the present work, respectively.

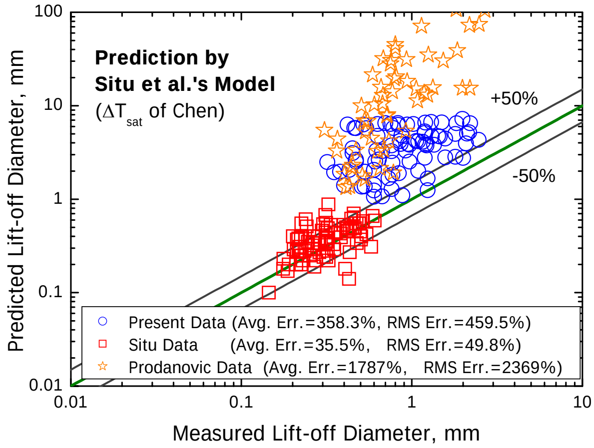

Fig. 1 Prediction results of Situ et al.'s model.

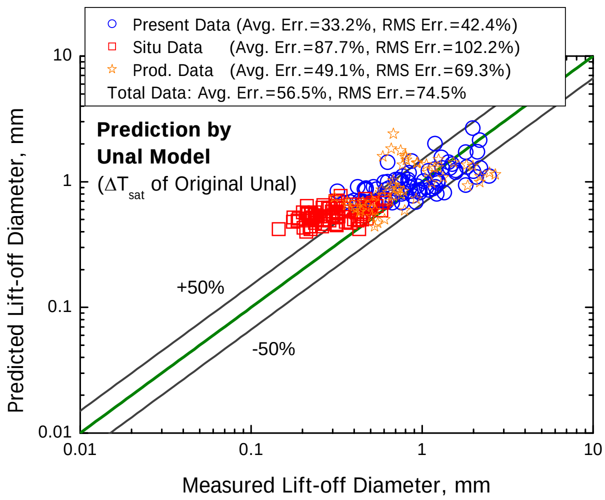

Fig. 2 Prediction results of original Unal's model.

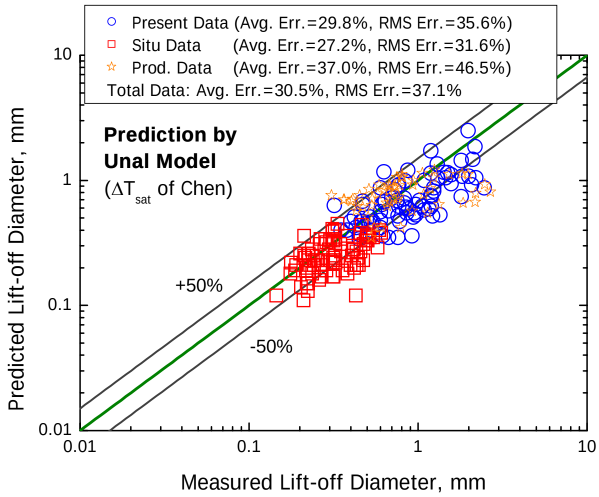

Fig. 3 Prediction results of modified Unal's model.

3. Conclusions

The bubble lift-off diameter and the bubble nucleation frequency showed a stochastic nature and they competed with each other in consuming the thermal energy from the heated surface. $f_b{*}D_{lo}^2$ showed clear tendency with the change of subcooling, mass flux, and heat flux. Among the existing models for the bubble lift-off diameter or the maximum bubble diameter, the modified Unal's model showed the best prediction results. The prediction error of this model was excellent considering the stochastic nature of the bubble lift-off diameter.

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