

Visualization and Modelling of Pool Boiling Bubble Growth and Departure

Anuj Sethia

IIT Bombay

Email: anujsethia66@gmail.com

Amrita Birhman

IIT Bombay

Email: amritab31@gmail.com

Janani Srree Murallidharan

IIT Bombay

Email: js.murallidharan@iitb.ac.in

Abstract

Bubbles of different sizes were generated, and their growth and departure characteristics were studied. Data for very high subcooling that is not available in literature, were generated. A bubble growth and departure model was developed and preliminary results indicate improved bubble departure prediction capabilities across a wide range of subcooling.

I. INTRODUCTION

Boiling heat transfer has been a major topic of study for several decades due to the central role it plays in the heat transfer achieved by industrial systems like pressurized Water Reactors (PWRs) etc. Its study has added importance due to its capability to also trigger safety-crisis related events, such as the 'Critical Heat Flux' (CHF) condition. The CHF-like condition is mainly triggered by accumulation of bubbles at the heater surface, which results in a significant increase of local wall temperature, eventually leading to its failure. Thus, understanding the near-wall vapour dynamics becomes central to designing safe and efficient industrial systems.

A. Experimental studies on wall-bubble growth

The formation of bubbles and their effect on the rate of heat transfer is a complex phenomenon and depends on many parameters such as bulk temperature, working pressure etc. However, a review of literature reveals that parametric dependence on some factors have been explored more than others. An important parameter is liquid subcooling and several experiments on subcooled flow boiling have been performed. A detailed review of literature is provided in Goel et al. [5]. However, some fundamental aspects of the phenomena have still not been understood, and must be studied in a simple framework. Thus, in this study, experiments of high subcooled pool boiling from natural nucleation sites have been performed. Surprisingly, studies looking at bubble dynamics in subcooled pool boiling are sparse, and hence this study also serves to add crucial data to existing literature.

Additionally, in this phenomena, it has been observed that different sized bubbles are formed on a single surface at a specific operating condition, however no study has looked into the fundamental similarities/differences between these bubbles. In this study, we have also generated different bubble sizes on a single strip (of varying width), and analyzed how they differ in their bubble characteristics.

B. Modelling studies on bubble growth

Models for Bubble departure and lift-off have been developed for a wide range of boiling conditions (Klausner et al. [1] and [2], Goel et al. [5]). However, most of the models were developed and tested for flow boiling conditions. Hence, in this paper, a preliminary version of the model is presented which can predict both subcooled and saturation bubble growth and departure for a wide range of pool boiling conditions.

II. METHODOLOGY

A. Experimental details

The sample geometry was chosen to be a uniquely designed double dog-bone shape which creates different heat flux in the different sections of the sample with the sample power input (Figure 1).



Figure 1: The test section

The sample was placed in a cylindrical glass container (200 mm X 100 mm) completely filled with distilled water. The desired bulk temperature was maintained using a separate 1 KW bulk heater. All the experiments were conducted at atmosphere pressure conditions. Only natural nucleation sites were focused for measurements. K type thermocouple was used to measure the bulk temperature of the water with an accuracy of 0.09°C. Visualization of bubbles was done using a SA5 Photron at 50-1000 fps and at a resolution of 1024 X 1024 pixels using a 90 mm f/2.8 Tamron Macro Lens. Bowens

Gemini 1000 pro mono light was used as a light source. Various experiments were performed at different heat flux, and at different subcooling ranging from 20 to 65 k to capture the bubble dynamics.

B. Bubble Growth Model

Factors affecting bubble growth rate are pressure, saturation temperature, liquid to vapor density ratio, the heat flux, mass flux, wall temperature, thermal boundary layer thickness, contact angles, contact diameter etc. Present study is a modification on Mazzocco et. al. study [9].

$$R(t) = (K_{ML} + K_{PB})t^{0.5} \quad (1)$$

$$K_{ML} = 2 \frac{\pi^2 + 1}{\pi^2} Ja^{2.1} \sqrt{\frac{\eta_l}{Pt_l \pi}} \quad (2)$$

$$K_{PB} = 2 \sqrt{\frac{3\eta_l}{\pi}} Ja^{2.125} \quad (3)$$

where, K_{ML} is the growth due to the evaporation through micro-layer beneath the bubble and K_{PB} is the bubble growth due to the evaporation from the surrounding liquid. Ja is the Jakob number of the fluid and η_l is the liquid thermal diffusivity and Pr is the liquid Prandtl number. The exponent to the Jakob number is estimated using various bubble growth experiments done independently by others. The formulation is established on a certain portion of the data while its predictions were tested on another set. For subcooled boiling an additional subcooling factor (χ) is also multiplied to the growth rate, where $\chi = (T_{wall} - T_{sat}) / (T_{sat} - T_{bulk})$. This incorporates the condensation due to subcooled region.

C. Force Balance Model

Klausner et al. [1] modelled the bubble force dynamics for pool boiling using the basic forces like the surface tension, buoyancy, contact force and the growth force. All these forces act in the direction normal to the surface in pool boiling. The lift force on the bubble due to other bubbles is eliminated here assuming only single bubble at the nucleation site at any specific time instant.

$$\Sigma F_y = F_s + F_b + F_{cp} + F_G \quad (4)$$

$$F_G = \rho_L \pi R^2 (10R_1^2 + RR_2) \quad (5)$$

Where, R_1 and R_2 are the bubble radius as a function of time, first derivative of R , second derivation of R with respect to time respectively. Though this study aims to analyse bubble growth and departure for pool boiling conditions, the authors also compared the model developed with existing flow boiling data.

III. RESULTS AND DISCUSSION

A. Bubble Growth Visualization

Two distinct bubbles were successfully generated, on the same test section, for the same input power, and a subcooling of 43 K, with approximate departure diameters of 1.717 mm and 0.59 mm. One bubble formed consistently at the notch, and another larger bubble, formed at the wider portion of the nichrome strip. Continuous bubbles were observed to form and depart at each of these natural nucleation sites. In fact, burn marks representing the bubble base diameter appeared on the specimen due to the high heat transfer achieved at the contact line of the bubble. This can be seen in Figure 2. Figure 3 shows the growth of bubbles formed at the

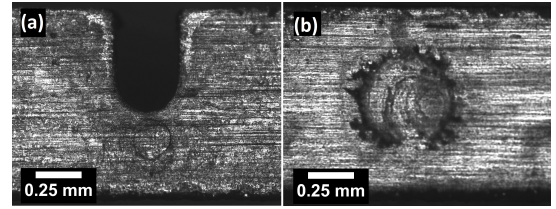


Figure 2: Base diameter of small and large bubble notch. The operating conditions were a input heat flux of 0.35 W/mm^2 at the notch, and a subcooling of 28.6, 38.6 and 43.9°C . The last image of each series shows the bubble at its departure size.

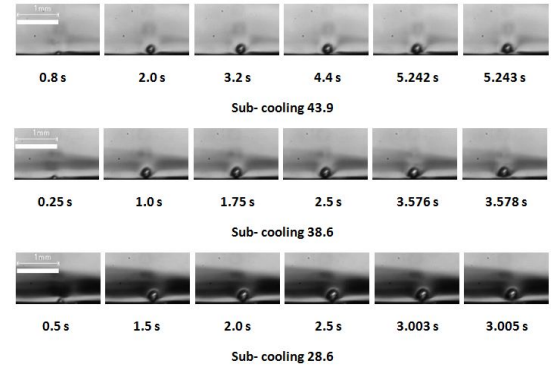


Figure 3: Images of growth and departure at notch

Figure 4 plots the bubble growth and departure for the various subcooling temperatures. It can be seen that, a smaller initial size of nucleating bubble can be captured for the case with the highest subcooling (43.9 K). This can be explained as follows. Bubble growth has two phases: inertia-controlled growth followed by heat-diffusion controlled growth. The growth rate for the former is faster compared to the latter. At lower subcooling (increased bulk liquid temperature) the thermal boundary layer near the wall is thicker, and this ensures stronger inertia-controlled growth. This phase is too fast to be captured by the present camera, and hence the first bubble

size that can be captured is when the bubble growth starts to slow down i.e. transition to heat-diffusion controlled growth. At very high subcooling, due to the presence of a much thinner thermal boundary layer, the bubble does not have a significant inertia-controlled growth phase, and a smaller size can be captured owing to an earlier onset of heat-diffusion controlled growth. It is to be noted that

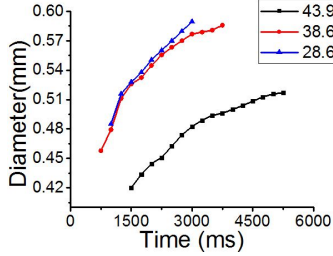


Figure 4: Plot of bubble growth at notch

for low subcooling temperatures, though the initial sizes are different as explained above, the difference in growth rates almost disappears (38.6 K and 28.6 K). It is also to be noted that the time to attain the departure sizes of these bubbles has decreased with subcooling. Based on this observation we conclude that the initial size up to which the inertia-controlled growth occurs is an important contributor towards the bubble departure size, and its departure time. If the size reached in inertia-controlled growth phase is larger, then the buoyancy force is larger aiding faster departure. Though the growth rate is nearly same, the growth force would also be influenced due to this larger initial size. Similar imaging of the larger bubble was also performed. The larger bubble also displayed similar growth characteristics as the smaller bubble. The larger bubble however displayed much slower growth compared to the smaller bubble. The smaller bubble, appeared to pop-up suddenly on the strip and then subsequently grow with heat-diffusion controlled growth. Thus we hypothesize that the inertia-controlled growth phase of the larger bubble contributes lesser to the departure of the bubble compared to the small bubble.

B. Model Predictions

The proposed model has been tested on different experimental datasets of pool boiling of water, both from literature, as well as, with the data generated in the present study: Klausner [1] (8 Data Points), S.H. Kim [6] (5 Data Points), S. Michaie [4] (58 Data Points), Pasquini M.E [7] (25 Data Points), Present study (35 Data Points). Figure 5 shows how the model predictions (solid line) compares with the experimental growth rates (dots) of the two distinct bubbles as measured by the

experiments. Fig. 5(a) is for the smaller bubbles growing at the notch while Fig. 5(b) is for the large bubbles. 'T' in the figure represents the actual bulk fluid temperature. In Fig. 5(a), the experimental data indicates that the smaller bubbles' growth rate mainly corresponds to heat diffusion controlled growth. The initial portion of inertia controlled growth was too fast and could not be captured through the optical cameras at the current fps. However, in Fig. 5(b), one can see that the transitioning from inertia controlled growth to heat diffusion controlled growth could be captured. The experimental data also shows that smaller bubbles though growing at a slower rate than the larger bubbles, depart much faster than the larger bubbles. For example, for $T = 71^\circ\text{C}$, the small bubbles depart by 2.5 sec while the larger bubbles depart at approximately 25 secs. Note: The last dot indicates the experimental bubble departure size, while the cross at the end of the solid line indicates the model's prediction of departure.

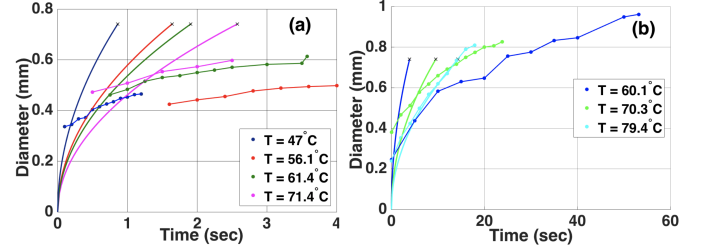


Figure 5: Growth rate prediction of (a) small and (b) large bubbles at different Heat Flux

From the predictions of the growth rate model the following can be concluded:

- The model predicts with better accuracy growth rate at low subcooling. This is observed both for the large and small bubbles.
- The growth rate model when applied to the large bubble cases appears to adhere close to the growth rate in the initial stages, while this is not the case for the smaller bubbles. Hence, it appears that the growth rate being modelled by the present model is the transition growth rate i.e. when bubbles transition from inertia to heat diffusion controlled growth, and is not a pure heat diffusion controlled growth. There is a $\sqrt{t}$ dependence in the present model indicating heat diffusion controlled growth, however, there appears to be some other term which is accelerating the growth rate. Modification of the model to capture the appropriate regimes are underway.
- The model predicts higher growth rate to what is observed in experiments. The same reason as

given above can be attributed to this behaviour.

- The model predicts that growth rate increases with increase in subcooling, while the reverse is observed in experiments. This might be because the condensation effects on bubble growth rate during heat diffusion controlled growth have not been properly captured by the model. Modifications are being done to incorporate this specific aspect into the model.
- The model predicts an earlier departure for both the large and small bubbles. As an extension of the previous points, and looking at the force balance equation, it can be concluded that a higher growth force prediction, in turn generates a higher buoyancy force and thus would cause an earlier departure. This is indeed what is observed in both cases.
- The model overpredicts the departure diameter for the small bubbles, and underpredicts it for large bubbles. This is indeed interesting as, though growth rate is overpredicted in both cases, the departure diameter predictions are opposite for both cases. We hypothesize that this is related to the contact line movement on the heater surface and the associated surface tension force.

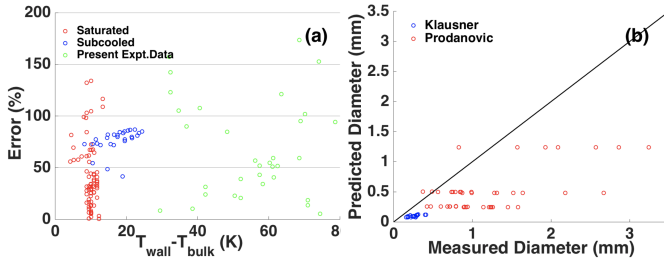


Figure 6: Departure diameter prediction for (a) Pool and (b) Flow boiling

Figure 6 shows performance of the present model over the whole spectrum of pool boiling datasets. Very high subcooled pool boiling data is not available in literature. This has been obtained in the experiments performed in this study (green dots in Figure 6), and the bubble departure diameter model's predictions has been compared against it. The model predicts well for saturated boiling conditions, with a large number of predictions falling under 40% deviation. Most of the predictions for low subcooling data fall within 40-80 % deviation. There is equal scatter about 60 % for the deviations of high subcooling data. These error percentages across the wide range of subcooling is better than the performances of other models previously discussed in the literature review

section. Further modifications that are being undertaken would likely improve the predictions. The model was also tested against the flow boiling experimental data of Klausner et al. [2] and Prodanovic et al. [3]. From the fig. 6(b), it is clear that the model under predicts the departure diameter. The predictions are better for small bubbles than for larger bubbles. This deviation might be primarily due to the growth rate being tuned for pool boiling conditions. Some more work on flow boiling would improve the model's predictability.

IV. CONCLUSIONS

On the whole, there is a lack of data that actually mimics reality, i.e. boiling from natural nucleation sites at high subcooling conditions (similar to reactor conditions). The experiments performed in this study addresses this lacunae and provides an understanding of the effect that the initial growth characteristics has on bubble departure. The model developed in this paper shows improved prediction capability across a wide range of subcooling. Further aspects that need improvement have been identified and are being addressed.

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