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Ignored/Intriguing Processes Involved During Bubble Lift-Off Stage in Flow Boiling

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Abstract – Traditionally the bubble departure and/or lift-off processes have been predicted based on force balance approach. However, recent experiments dedicated towards fundamentally understanding the pool and flow boiling have revealed severe limitations in the force balance approach towards accurately predict either bubble departure or bubble lift-off. In fact, the bubble lift-off process is very complex in flow boiling, involving asymmetric depletion of microlayer and rewetting of dry patch, it was poorly understood, mainly due to the limitations of measurement techniques. Our experimental measurements using state-of-the-art visible wavelength light-based imaging techniques – thin film interferometry and rainbow schlieren deflectometry–revealed many interesting and complex phenomena during the lift-off process. Among the many observations made, two phenomena highlight the complicated nature of boiling process and warrant proper discussion. First, the phenomenon of rapid ejection of bubbles in the normal direction to the heater surface (without sliding), almost perpendicular to the direction of buoyancy. Second, the appearance of bubble on the heater surface from the side-view, but with no real contact with the heater surface (as indicated by thin film interferograms). Particularly, the first phenomenon captured by thin-film interferograms revealed an intriguing pattern: an unusual depletion of microlayer from the downstream direction. To the best of our knowledge, such a phenomenon has not been reported/explored prior to this work.

Keywords**:** Microlayer dynamics, Flow boiling, Ejecting bubbles, Thin-film interferometry

1. Introduction

Boiling heat transfer, which is recognized for its effective heat transfer capability with minimum temperature gradient, has attracted a wide range of applications, from its use in nuclear reactors to electronic equipment. However, due to limited understanding of the fundamental processes involved in boiling, the design of the systems still relies on empirical correlations with very high safety margins. For instance, prediction of bubble dynamics parameters– bubble departure diameter and frequency, which are essential for component scale modeling involving heat flux partitioning, is premised upon force balance approach. However, recent experiments in both pool [1] and flow boiling [2] conditions revealed that force balance approach suffers from severe limitations and it is inapplicable to accurately predict either bubble departure or bubble lift-off. Moreover, microlayer (a thin trapped liquid layer underneath the bubble) dynamics – spread and thickness – are important in calculation of bubble growth rate. Inaccurate models are mainly due to lack of experimental data examining the fundamental processes of boiling, which have wide range of spatial and temporal scales. Particularly, to understand the bubble departure and lift-off dynamics, the process needs to be studied at multiple length scales ($O(10^{-2}\sim10^{-3}m)$ of bubble dynamics and $O(10^{-6}m)$ for microlayer dynamics) simultaneously. In the last few years, such detailed studies are being carried out both in pool and flow boiling conditions [3]–[5]. In our previous works, we have reported bubble, microlayer and dry patch dynamics involved in flow boiling for single [2], [3], [6], [7] and multiple nucleations [8].

During the initial stage of bubble growth, microlayer expands symmetrically in all directions even in flow boiling. However, after the reduction in growth rate, the bubble base starts to recede, as does the microlayer [2], [3], [6]. Usually, the microlayer depletes from upstream direction due to the combined effect of flow inertia and capillary force and from the centre due to the expansion of dry patch, which is driven by evaporation on hydrophilic surface. This depletion mechanism is observed in bubbles that slide from its initiation site and subsequently lift-off from the surface. Nevertheless, we observed that when the flow rate is decreased to about 4 lph (*Re* ~500), many bubbles ejected from the heater surface in the normal direction, almost perpendicular to the flow and buoyancy directions. In this study, we investigate the rapid ejection of bubbles in the normal direction using state-of-the-art visible wavelength light-based imaging techniques, namely thin film interferometry (TFI) and rainbow schlieren deflectometry (RSD). We report intriguing phenomena observed during the lift-off process, including the depletion of the microlayer from the downstream direction and the absence of a dry patch, even though the bubble appears to be on the heater surface from side-view videography.

2. Experimental section

2.1. Flow boiling setup

Figure 1 depicts the schematic diagram of the test channel employed for conducting flow boiling experiments in a vertical orientation. De-ionized (DI) water served as the working fluid in these experiments. The boiling channel comprises four stainless steel plates assembled together to create a rectangular passage with a cross-section measuring 5 mm × 10 mm and a total length of 750 mm. The inner walls of these plates have been diamond polished to avoid the nucleation of bubbles at random locations. One of the walls of the test section is fixed with a heating substrate of length 200 mm, width 10 mm and a thickness of 1.1 mm. The heater is placed at a distance of 400 mm from the inlet of the test section and is made of glass substrate. A resistive ITO (indium tin oxide) coating has been provided only on one side of the glass substrate to achieve heating for the boiling experiments.

In order to have a controlled single vapour bubble nucleation, the ITO film was partially etched in a semi-circular fashion resulting in a neck formation with a width of 3 mm. This particular exercise helps increase the local electrical resistance, subsequently resulting in the nucleation of a single vapor bubble at the etched region only. Three transparent glass windows of high optical quality of length 75 mm (indicated in cross sectional view) were mounted on the other three walls of the channel at a distance of 450 mm from the inlet.

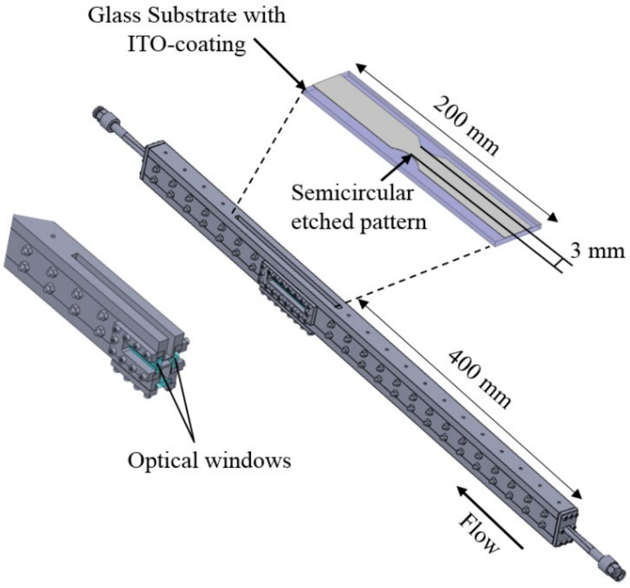

Fig. 1: Flow boiling channel and its various components.

2.2. Optical layout

Figure 2 shows the schematic representation of the optical configuration of the TFI and RSD based videography. In order to capture the dynamics of microlayer, TFI has been employed.

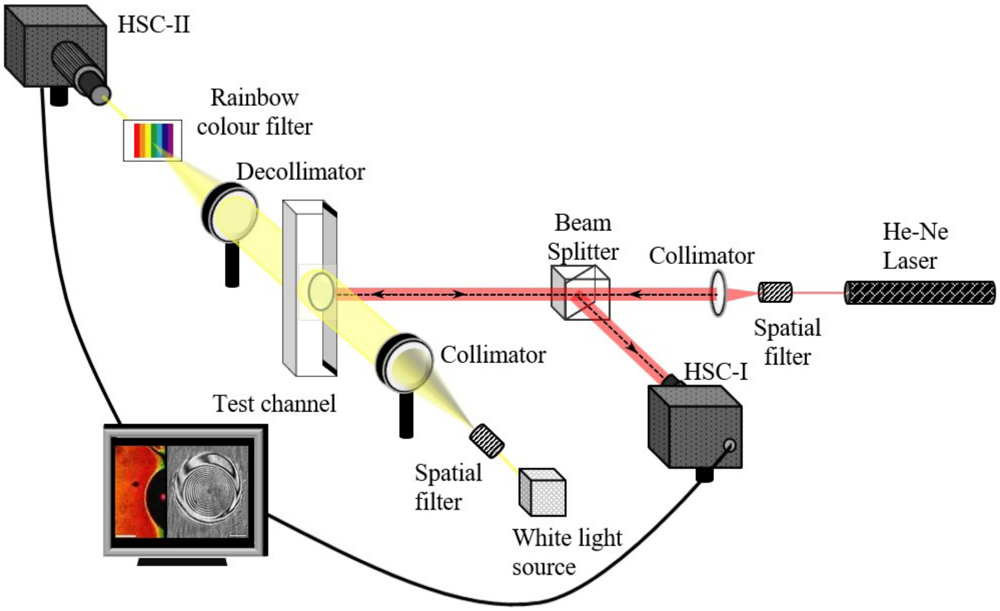

Fig. 2: Optical layout for TFI and RSD based videography. ("Reproduced from [6], with the permission of AIP Publishing")

The optical arrangement of TFI consists of a He–Ne laser (632.8 nm) as the light source, a spatial filter and a beam splitter. The light emerging from the laser source has first been collimated using the spatial filter and collimating lens. The collimated light beam of size 20 mm thus obtained is allowed to pass through the beam splitter and then directed to fall exactly on the nucleation site from the back side of the heater surface as shown in the figure. As the light beam passes through the bubble base, a part of the light beam gets reflected from the heater surface-liquid interface, while the remaining transmitted part of the light beam gets reflected at the liquid-vapour interface. These two reflected light waves interfere and travel back through the beam splitter, where they are reflected towards the camera screen. The high-speed camera, HSC-I, with a telecentric zoom lens of ×12 was configured with the interferometer to capture the microscopic dynamic behaviour of the microlayer during the growth and detachment process of the vapour bubble. The dynamic movement and structure of the microlayer have been recorded at the rate of 10,000 frames per second (fps).

Rainbow schlieren-based high-speed videography in synchronization with TFI was employed to map bubble dynamics with a spatial resolution and temporal resolution of 7.75 μm/pixel and 5000 fps, respectively, using HSC-II. This imaging technique provides a significant color contrast between the vapor bubble and bulk liquid, which enables a clear distinction of the vapor–liquid interface. Further information regarding this imaging technique can be located elsewhere [4].

3. Results and discussion

Flow boiling experiments were conducted in a vertical rectangular channel at flow rates of 4 lph under the subcooling conditions of 2 K. Mapping of the bubble dynamics and the corresponding microlayer dynamics is done using RSD based high-speed videography (at 5000 fps) and TFI (at 10000 fps).

The simultaneous evolution of both bubble and microlayer dynamics is presented in Figure 3. Consistent with the previously reported observations on microlayer [2], [3], [6], it has been observed that the microlayer grows radially outward (almost symmetrically) during the initial stage of bubble growth (for instance, at $t = 0.9$ ms in Figure 3). During the initial growth phase, a vapor bubble formed underneath the superheated liquid layer (indicated by the green color in the schlieren image). This phenomenon can also be observed at $t = 0.9$ ms, where more than half of the vapor is in contact with the superheated liquid layer.

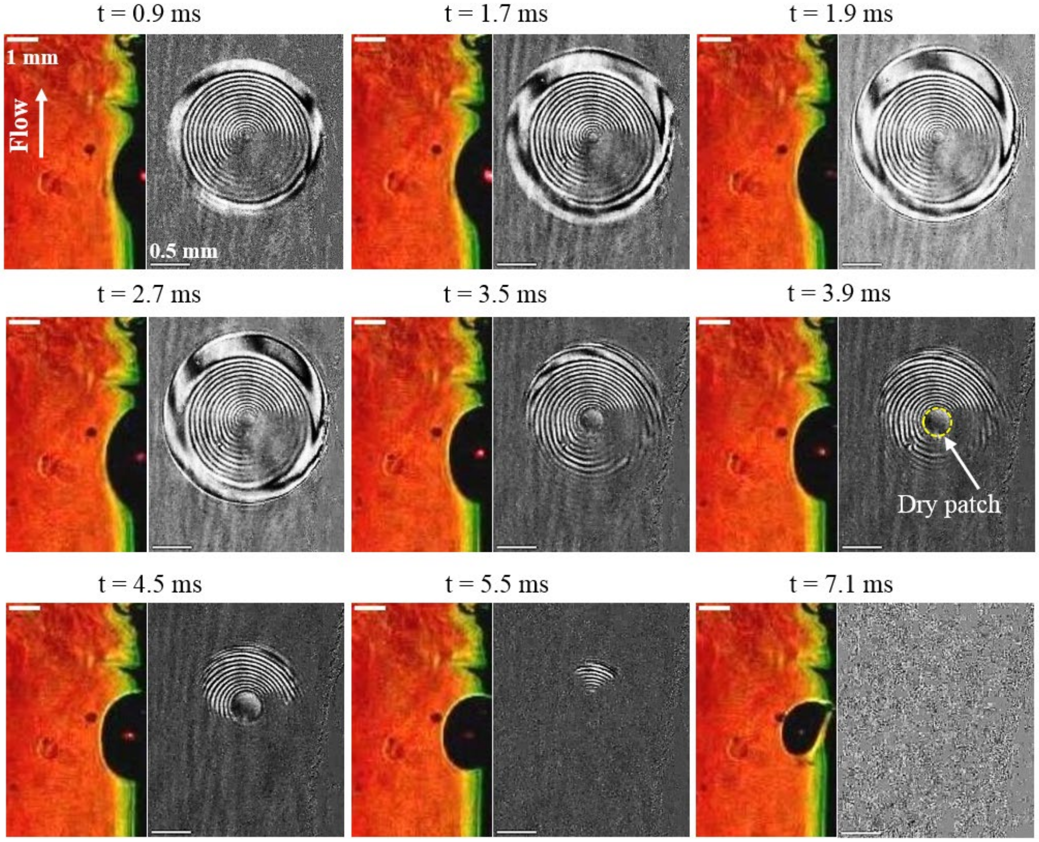

Fig. 3: Bubble and microlayer dynamics at various time instants.

After this growth phase, the microlayer begins to deplete from the upstream direction. In the bubble cycle depicted in Figure 3, the microlayer appears to have significantly depleted from the upstream direction at $t = 3.5$ ms. As the growth rate decreases, it is not sufficient to maintain the growth of microlayer spread [2], and the upstream depletion of the microlayer can be attributed to the combined effect of flow inertia and capillary force, a topic extensively covered in our recent publications [2], [8]. Interestingly, the depletion of the microlayer from the downstream edge was also observed at $t = 3.5$ ms. Figure 4 clearly indicates the depletion of the microlayer from both upstream and downstream directions (from $t = 3$ to 5 ms). This phenomenon contrasts with previous studies [3] on flow boiling (at high flow rates ($Re \sim 2400 - 5000$)), where depletion from the downstream side was not observed.

As highlighted in Figure 4, the decrease of microlayer spread, even in downstream direction is significant. Nevertheless, the rate of depletion in the upstream direction appears to be higher than in the downstream direction, a trend anticipated due to the influence of bulk flow. This observation is particularly significant since the microlayer plays a crucial role in bubble growth following its initial growth phase driven inertia. This behavior can be rationalized as a result of capillary forces; that is, in the absence or minimal presence of other forces, the bubble tends to become more spherical. However, it remains challenging to explain why the bubble size is smaller at a higher flow rate (Re ~2400) (Re ~2400) [6]. Particularly, after the initial growth-phase, the dynamics of the bubble are different from those reported in earlier studies. This discrepancy mandates the need for a more detailed experimental analysis that incorporates temperature measurements alongside microlayer dynamics. To authors' best knowledge, no existing study describes this phenomenon of microlayer depletion in flow boiling.

In addition, the dry patch (actual contact of vapor bubble to the heater surface) also increases with time till 4.5 ms then then it started decreasing. At *t* = 4.5 ms the microlayer depleted completely from the upstream direction, at this instant the the dry patch undergoes rewetting. After the dry patch is fully rewet at *t* = 5.5 ms, this moment – when the dry patch disappears – also represents the actual lift-off of the vapor bubble from the heater surface. However, from the RSD image at image at *t* = 5.5 ms it appears as if the bubble is in contact with the heater surface. This is one of the aspects that can lead to failures in model development when only side-view videography is used to analyse the lift-off process. This aspect has also been highlighted in our previous works [2], [3]. Finally, when the vapor bubble lift-off from the heater surface at *t* = 7.1 ms (based on RSD image), the microlayer disappears.

These observations highlight the unexpected behaviours in flow boiling, and we also emphasize that in traditional models these phenomena were never acknowledged.

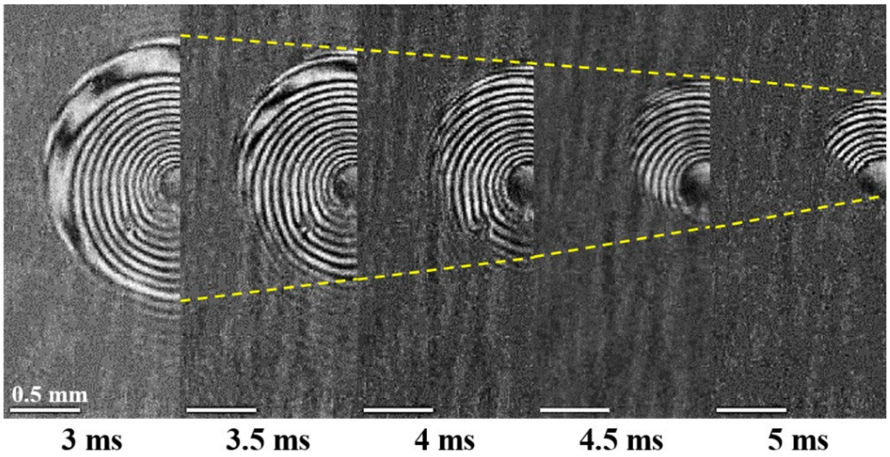

Fig. 4: Bubble and microlayer dynamics at various time instants.

4. Conclusion

In this study, we unveiled intricate phenomena during the bubble lift-off process in flow boiling using thin-film interferometry and rainbow schlieren deflectometry, emphasizing the complexity of the boiling process. Notably, the rapid ejection of bubbles in a direction almost perpendicular to buoyancy, paired with an unusual microlayer depletion pattern, underscores the need for a deeper understanding and re-evaluation of existing models. To the best of the authors' knowledge, no existing model acknowledges the existence of such a phenomenon. Moreover, this work highlights also the actual lift-off moment and emphasizes that existing force balance models cannot explain this behaviour. Future research should focus on deeper understanding of these newly observed phenomena, which will potentially lead to more accurate predictive models and a comprehensive understanding of boiling dynamics.

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