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EXPERIMENTAL STUDY OF INTERACTIONS BETWEEN WAKES AND NUCLEATE BOILING IN INTERMITTENT FLOW PATTERNS

Xiang Zhang, Alexander S. Rattner*

The Pennsylvania State University, University Park, PA 16802, USA

ABSTRACT

Extensive research has been conducted to resolve small-scale microlayer and bubble nucleation and departure processes in flow boiling, building on controlled pool boiling studies. Large-scale two-phase flow structures, such as Taylor bubbles, are known to locally modify transport due to their wakes and varying surrounding liquid film thickness. However, the effect of interaction of such large-scale flow processes with bubble nucleation is not yet well characterized. Wakes may drive premature nucleating bubble departure, or conversely, suppress boiling due to boundary layer quenching, significantly affecting overall heat transfer. To explore such phenomena, a two-phase flow boiling visualization facility is developed to collect simultaneous high-speed visualization and infrared (IR) thermal imaging temperature distribution data. The test cell channel is 420 mm long with a 10 mm × 10 mm internal square-cross section. A transparent conductive indium tin oxide (ITO) coated sapphire window serves as a heater and IR interface for measuring the internal wall temperature. The facility is charged with a low boiling point fluid (HFE7000) to reduce uncertainties from heat loss to the laboratory environment. Vertical saturated flow boiling wake-nucleation interaction experiments are performed for varying liquid volume flow rates (0.5 – 1.5 L min^{-1}, laminar-to-turbulent Re) and heat fluxes (0 – 100 kW m^{-2}). Discrete vapor slugs are injected to explore interactions with nucleate boiling processes. By measuring film-heater power, surface temperature distributions, and pressures, local instantaneous heat transfer coefficients (HTC) can be obtained. Results will be applied to assess simulations at matched conditions for void fraction, and size statistics of flow structures.

KEY WORDS: Flow boiling; Intermittent flow; Wake-nucleation interaction; Heat transfer enhancement

1. INTRODUCTION

The vertical-upward slug flow pattern is a quasi-periodic two-phase flow pattern that occurs over a broad range of flow scales, with applications including oil and gas operations, bubble pumps, refrigeration systems, and desalination [1]. In flow boiling, a major portion of phase change heat transfer can occur at the smallest scales: in 1 nm – 10 μm thick liquid microlayers under nucleating bubbles [2], which can have site densities of 10^4 – 10^6 cm^{-2} [3]. Theoretical closure models have been proposed for individual bubble nucleation, growth, and departure processes due to hydrodynamics [4]. However, translation of such results to full channel flows has proven challenging due to multiscale interactions between two-phase flow structures and the physical complexity of phase change process. Studies have been performed to quantify heat transfer enhancement in the wake of rising Taylor bubbles [5], [6], but interactions between wakes and nucleate boiling are not well characterized.

In the present study, a two-phase flow boiling visualization facility was built to provide local visualization and temperature distribution data for developing intermittent flow boiling, as well as the wake-nucleation interactions. The test cell channel is a 420 mm long 10 mm square-cross section transparent polycarbonate tube. A transparent ITO coated sapphire window was developed that directly heats the inside wall of the flow channel. The facility was charged with HFE-7000 (34°C normal boiling point) to allow flow boiling measurements with minimal heat loss to the surroundings. Both high speed imaging (shadowgraphy) and

*Corresponding Author: Alex.Rattner@psu.edu

high speed thermal imaging were used to capture the nucleate flow boiling visualizations and temperature profiles of the heating surface. Vertical saturated flow wake-nucleation interaction experiments were performed for different volume flow rates (0.5 – 1.5 L min^{-1}) and heat fluxes (0 – 100 kW m^{-2}). These experiments span laminar to turbulent flow conditions (Re = 800 – 9100). Inlet flows to the observed section were in the bubbly regime, and discrete vapor slugs were injected upstream. By measuring film-heater power, surface temperature distributions, and pressures, local instantaneous heat transfer coefficient (HTC) could be obtained. Results will be applied to assess simulations at matched conditions for void fraction, and size statistics of flow structures.

2. EXPERIMENTAL FACILITY

A two-phase flow boiling visualization facility was built to provide local visualization and temperature distribution data for developing intermittent flow boiling, as well as the wake-nucleation interactions. A schematic of the flow boiling facility and physical configuration of test cell is illustrated in Fig. 1.

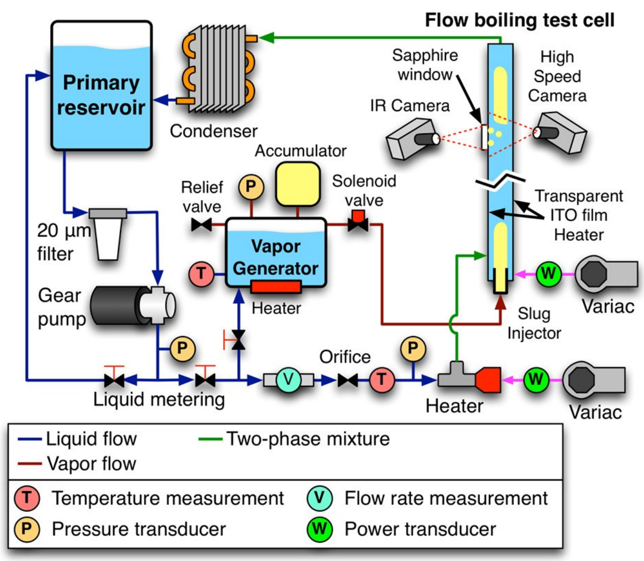


Fig. 1 Schematic of flow boiling facility and test cell.

The experimental facility consisted of a primary reservoir, condenser, gear pump, liquid flow meter, vapor generator, solenoid valve, preheater, test section, and DC power supply. The facility was charged with 3M Novec HFE-7000 (T_{sat} (P_{amb}) = 34°C, h_{LV} = 143 kJ/kg) to reduce uncertainties from heat loss to the ambient and also enable high flow quality experiments. A preheater ~ 1 kW was installed downstream of the liquid flow meter to condition the test cell inlet to specified working qualities and fluid temperatures. A vapor-generating chamber was installed with a process-controlled heater to inject individual vapor slugs through a solenoid valve into the test cell. The test cell is a machined acetal plastic frame enclosed by two clear polycarbonate panels, which form a 420 mm long channel with a 10 mm × 10 mm internal square-cross section. Fluid was resistively heated in a portion of the channel by an inset sapphire disk with a transparent Indium tin oxide (ITO) film strip on the wetted face. This arrangement permits direct optical visualization of the nucleate flow boiling process and thermal imaging of the inside heated wall. Visualizations were collected with a high-speed camera (Phantom Miro Lab340, Vision Research). Heat transfer measurements were obtained by an ImageIR 8300 (Infratec) thermography camera.

3. NUCLEATE FLOW BOILING

Fig. 2 presents measured bubble cycle wait and growth time at varying heat fluxes for a representative nucleation site. The overall bubble cycle and wait times scaled inversely with heat flux. With the increase of heat input, bubble cycle and wait time decreased rapidly, then stabilized to approximately the growth time. When large bubbles grew on closely neighboring nucleation sites, they affected the bubble growth dynamics, which led to some outlier measurements. In general, the overall bubble cycle time, wait time, and growth time were found to be insensitive to mass flux.

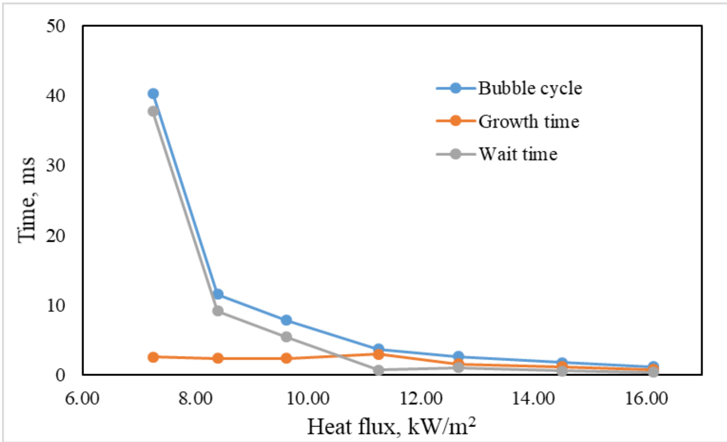


Fig. 2 Overall bubble cycle time, wait time, and growth time for a representative nucleation site at varying heat flux.

The measured bubble departure diameters for different heat fluxes are shown in Fig. 3. Combining the instrumentation and bubble departure diameter detection method (image analysis), the total uncertainty of departure diameter was estimated at ~9%. Bubble departure diameter slightly increased with heat flux at low flux conditions, then stabilized at medium and high heat flux.

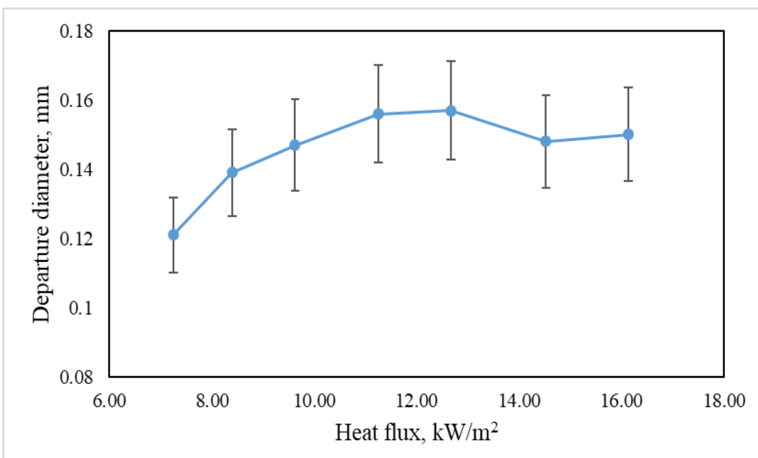
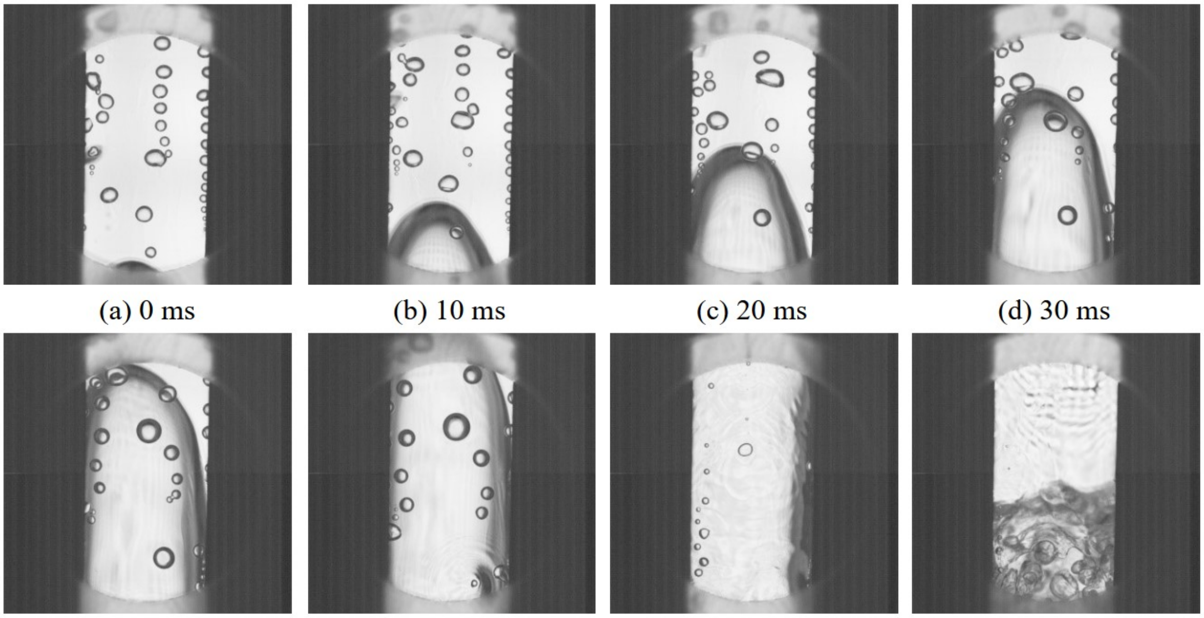


Fig. 3 Bubble departure diameters with heat flux.

4. WAKE-NUCLEATION INTERACTION

Fig. 4 presents the time sequence of a Taylor bubble passing through the measured window at a heat flux of 43.50 kW m^{-2}. During this period, some small nucleating bubbles merged with the large vapor slug. The thin liquid film around the Taylor bubble appeared to deactivate some nucleation sites during the event. This suggests that nucleate boiling contributions to heat transfer may be diminished in channel regions containing Taylor bubbles. As the Taylor bubble passed, its wake caused intense mixing and it was followed by a cluster of small slug bubbles. Preliminary thermal imaging data revealed a decrease in wall temperature in the Taylor bubble wake, indicating local heat transfer enhancement. Analyses of these shadowgraphy and thermal imaging data are ongoing to quantify the degree of transient heat transfer variations. Corresponding transient pressure drop measurements are of interest for future studies.



(a) 0 ms (b) 10 ms (c) 20 ms (d) 30 ms

(e) 40 ms (f) 50 ms (g) 150 ms (h) 270 ms

Fig. 4 Interactions between Taylor bubble and nucleation sites at heat flux of 43.50 kW m^{-2}.

5. CONCLUSIONS

In this study, a two-phase flow boiling visualization facility was developed to collect simultaneous high-speed visualization and IR temperature distribution data. Visualizations showed that both bubble cycle and wait time scaled inversely with applied heat flux. With increased heat input, bubble cycle and wait time decreased rapidly, then stabilized at approximately the growth time. Bubble departure diameters slightly increased with heat flux at the low flux range, then stabilized at higher heat fluxes. Interactions between Taylor bubbles and nucleating bubbles were also observed, including merging events and deactivation of nucleation sites in the film regions. Data analysis of these experiments is ongoing. In future work, measurements will be applied to assess flow boiling CFD simulations at matched conditions.

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