

Pressure Effects on Bubble-Base Growth and Microlayer Formation in Saturated Pool Boiling

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***Keywords :** Nucleate boiling; Microlayer; Pressure effect; Bubble-base growth; Wall boiling

1. Introduction

Microlayer dynamics occur at length and time scales far below the resolution of reactor-scale thermal-hydraulic simulations and therefore require closure when explicitly represented in wall-boiling models. The microlayer formed beneath a growing vapor bubble can contribute to bubble growth and wall heat transfer, and its formation is closely related to the motion of the liquid-vapor interface near the heated wall [1,2]. System pressure changes the thermophysical properties of the liquid-vapor system and strongly modifies bubble growth. Pressure-dependent experiments have also reported reductions in microlayer extent or lifetime as pressure increases [3,4]. However, how pressure-dependent changes in bubble-base motion are related to the radial extent and timescale of microlayer formation remains insufficiently quantified.

This study examines saturated pool boiling of water at 0.10, 0.15, 0.20, and 0.30 MPa using synchronized high-resolution laser interferometry (HRLI) and side-view shadowgraphy (SSG). The analysis distinguishes overall bubble growth from the radial motion of the bubble base and directly compares the bubble-base radius with the outer microlayer radius. The objective is to determine whether the pressure-dependent reduction in microlayer formation extent and duration is associated with the simultaneously measured bubble-base motion. Although the present pressure range is below light-water-reactor operating conditions, the resulting measurements provide controlled experimental evidence relevant to the development and assessment of pressure-dependent wall-boiling and microlayer models.

2. Experimental Method

Experiments were performed in a pressurized pool-boiling facility with saturated water. A transparent sapphire substrate coated with an electrically heated indium-tin-oxide film provided bottom optical access while generating isolated boiling bubbles. The nominal heat fluxes were 199.2, 216.6, 204.6, and 169.8 kW/m² at 0.10, 0.15, 0.20, and 0.30 MPa, respectively. Two bubbles were analyzed at each pressure, giving eight bubbles in total.

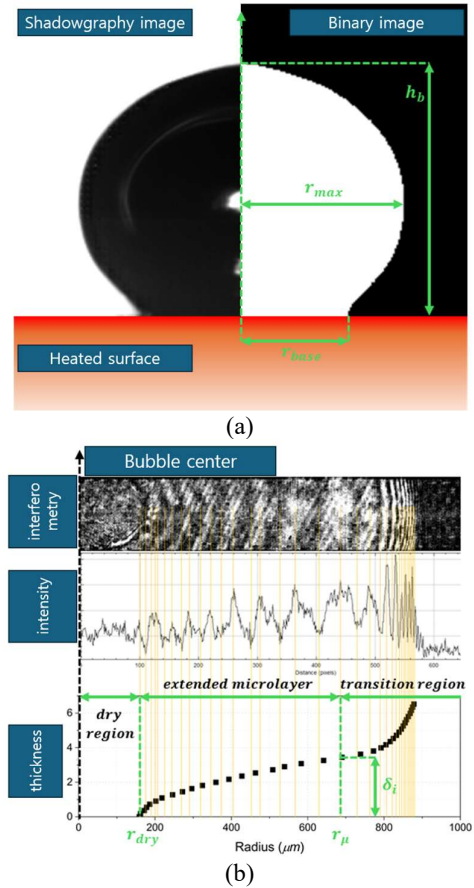


Fig. 1. Synchronized image-processing framework: (a) SSG-based identification of bubble geometry and bubble-base radius; (b) HRLI fringe/intensity processing and reconstructed near-wall interface profile.

HRLI and SSG were operated synchronously at 25,000 frames/s. HRLI resolved the bottom liquid-vapor interface at 1.62 μm /pixel, while SSG measured the macroscopic bubble contour at 27.17 μm /pixel. The HRLI fringe patterns were converted into interface-thickness profiles using the reconstruction procedure described in Ref. [5]. Figure 1 summarizes the two image-processing routes. The bubble-base radius, r_{base} , was defined from the radial position of the lowest discernible bubble-interface point in the SSG image and therefore represents an optically resolved bubble-base

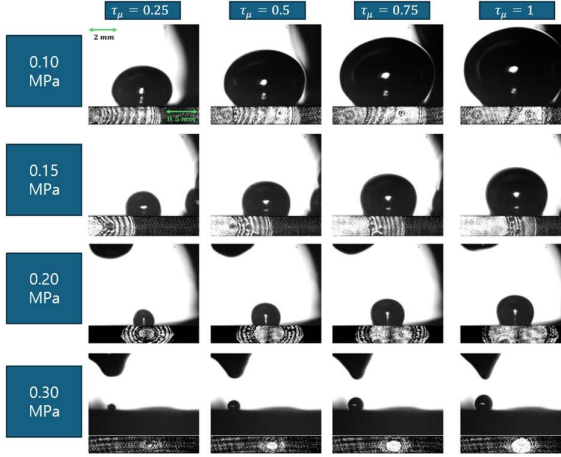


Fig. 2. Representative synchronized bubble (SSG) and microlayer (HRLI) evolution at equal normalized microlayer-formation stages for 0.10-0.30 MPa.

position rather than a microscopic contact line. The outer microlayer radius, r_μ , was defined from the HRLI profile at the boundary between the extended microlayer and the transition region. The maximum microlayer radius, $r_{\mu,max}$, and the corresponding time, $t_{\mu,max}$, were obtained when r_μ first reached its maximum. Frame-to-frame synchronization allowed r_{base} and r_μ to be compared at the same physical instant without temporal interpolation.

For visualization across cases with different formation durations, normalized time was defined as $\tau_\mu = t/t_{\mu,max}$. The local initial microlayer thickness was reconstructed separately from the measured post-formation thinning history.

3. Results and Discussion

3.1 Pressure-dependent bubble and microlayer growth

Increasing pressure reduced the bubble size and equivalent-radius growth rate. The same pressure ordering appeared in the near-wall motion: the radial distance reached by the bubble base during microlayer formation decreased markedly with pressure. Figure 2 shows representative synchronized bubble and microlayer images at equal normalized stages. Both the bubble and microlayer dimensions become progressively smaller with pressure, while the absolute time required to reach the same normalized stage becomes shorter.

The pressure-group mean bubble-base radius at the end of microlayer formation decreased from 1.60 mm at 0.10 MPa to 0.33 mm at 0.30 MPa. Over the same range, the mean maximum microlayer radius decreased from 0.934 to 0.154 mm, and the mean microlayer-formation time decreased from 6.06 to 0.66 ms. The endpoint quantities are summarized in Table I. In contrast, the local initial-thickness profiles showed substantial case-to-case overlap at common radii and no clear monotonic pressure ordering. The dominant pressure response was therefore a reduction in the radial extent and formation

Table I: Pressure-group mean endpoint quantities.

P (MPa)	$r_{base}(t_{\mu,max})$ (mm)	$r_{\mu,max}$ (mm)	$t_{\mu,max}$
0.10	1.603	0.934	6.0
0.15	1.331	0.836	3.96
0.20	0.747	0.410	1.36
0.30	0.326	0.154	0.66

time of the microlayer rather than a systematic change in its local initial thickness.

3.2. Bubble-base and microlayer kinematic relation

The synchronized measurements provide a direct comparison between r_μ and r_{base} . At all four pressures, r_μ increased monotonically with r_{base} , while the accessible radial range of both quantities contracted substantially with increasing pressure. Thus, the most consistent pressure-dependent change is the radial extent reached by the bubble base and microlayer edge rather than the emergence of a qualitatively different kinematic evolution.

Figure 3 summarizes the endpoint relations between system pressure, bubble-base growth, and microlayer formation. As shown in Figure 3(a), the bubble-base radius at the end of microlayer formation decreased

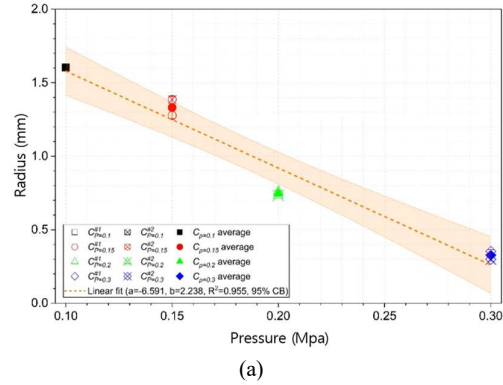
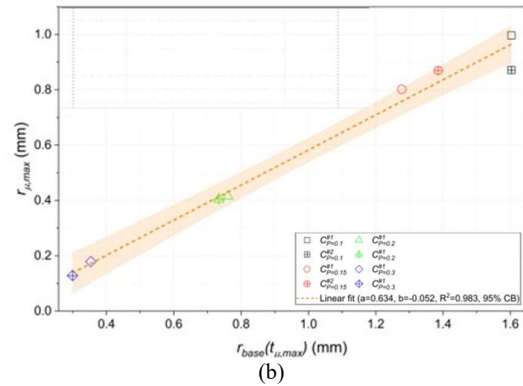


Fig. 3. Descriptive two-stage endpoint relations: (a) pressure dependence of the bubble-base radius at the end of microlayer formation; (b) relation between the maximum microlayer radius and the corresponding bubble-base radius. Shaded bands denote 95% confidence intervals.

systematically with increasing pressure and was well represented by a linear regression over the measured range ($R^2=0.955$). Figure 3(b) shows that $r_{\mu,max}$ was strongly correlated with $r_{base}(t_{\mu,max})$, with Pearson $r = 0.991$ and $R^2 = 0.983$. The two measured relations can be summarized by the following two-stage empirical description:

$$r_{base}(t_{\mu,max})[mm] = 2.238 - 6.591 P [MPa] \quad (1)$$

$$r_{\mu,max}[mm] = 0.634 r_{base}(t_{\mu,max})[mm] - 0.052 \quad (2)$$

These regressions describe the eight measured bubbles within 0.10-0.30 MPa and are not proposed as universal correlations. Both quantities vary with pressure, so the endpoint correlation alone does not establish causality. Nevertheless, the synchronized measurements identify bubble-base radial advance as a practical kinematic quantity associated with the pressure-dependent radial extent of microlayer formation.

The nominal heat flux was not identical among pressure conditions and the present dataset does not independently separate pressure and heat-flux effects. However, the heat flux did not vary monotonically with pressure, whereas the reductions in bubble-base and microlayer extent were systematic. The observed pressure ordering therefore cannot be attributed to the heat-flux variation alone.

3.3. Implications for pressure-dependent microlayer modeling

The present results have implications for pressure-dependent microlayer closures in wall-boiling models. Pressure strongly reduced the radial advance of the bubble base, the maximum microlayer radius, and the microlayer-formation time, whereas the local initial thickness showed no comparable monotonic ordering. A pressure-dependent microlayer treatment may therefore need to distinguish the local initial-thickness relation from the kinematic limits that determine the radial extent and duration of microlayer formation.

The present experiments are limited to 0.10-0.30 MPa and should not be extrapolated directly to reactor operating pressures. Rather, they provide a controlled basis for examining whether the observed bubble-base-microlayer relation persists under elevated-pressure, subcooled, and flow-boiling conditions [4].

4. Conclusions

Synchronized HRLI and SSG measurements were used to examine pressure-dependent bubble-base growth and microlayer formation in saturated water pool boiling from 0.10 to 0.30 MPa. Increasing pressure reduced overall bubble growth and strongly restricted radial bubble-base motion. The mean bubble-base radius at the end of microlayer formation decreased from 1.60 to 0.33 mm, while the maximum microlayer radius decreased from 0.934 to 0.154 mm and the microlayer-formation time decreased from 6.06 to 0.66 ms. At all pressures, the

outer microlayer radius increased with the bubble-base radius, while the radial range reached by both quantities contracted with increasing pressure; their endpoint quantities were strongly correlated. These results identify bubble-base radial advance as an experimentally accessible kinematic quantity associated with pressure-dependent microlayer formation. For wall-boiling modeling, the measurements indicate that the radial extent and formation time of the microlayer should be treated separately from its local initial thickness.

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