Experimental observation of the dynamic micro-and macro-layer during pool boiling

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Experimental observation of the dynamic micro- and macro-layer during pool boiling

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ABSTRACT
This paper presents the results of an experimental study on nucleate pool boiling. Experiments were performed using vapor-deposited thin films which were electrically heated. High-speed infrared and visible cameras simultaneously observed bubble growth from the heater surface. Possible experimental confirmation of microlayer dynamics is presented.

INTRODUCTION
Nucleate boiling is an extremely effective mode of heat transfer. It is used in many heat exchange and energy conversion systems. However, it is still a relatively poorly understood phenomenon. New experiments are necessary to enhance comprehension of boiling processes and close the knowledge gap.

This study provides state-of-the-art experimental data on variations of the local temperature and vapor-liquid interface at the heater surface. The study is part of an effort at MIT to gain a better insight into critical heat flux (CHF), particularly its enhancement in engineered fluids such as nanofluids (Buongiorno et al., 2008; Kim et al., 2007).

POOL BOILING FACILITY
A diagram of the facility used in this study is shown in Figure 1. A thin film made of Indium-Tin-Oxide (ITO) was directly heated. Boiling occurred on the upward facing side of this film which had an exposed area of 30x10 mm², and was 0.7 µm thick. The ITO was vacuum deposited onto a 0.4 mm thick sapphire substrate. This heater was connected to a DC power supply to control the heat flux at the surface. The cell accommodating the test fluid was sealed, included a condenser, and was surrounded by a constant-temperature water bath to minimize heat losses to the ambient.

To acquire the temperature distribution on the heater surface, an infrared (IR) high-speed camera was used to measure IR intensity. Simultaneous high-speed video (HSV) was taken with a high-speed digital imaging system. A function generator produces a transistor-transistor logic (TTL) pulse at 480 Hz which triggered both cameras to record an image allowing the synchronization of both cameras’ image sequences.

A dichroic (hot-mirror) was placed directly below the heater which reflects the IR (3-5 µm) spectrum to the IR camera and transmits the visible (400-700 nm) spectrum. The visible spectrum is then reflected by a silver-coated mirror to the HSV system. Thus, both cameras image the area of interest from the same point of view. The sapphire substrate is transparent to both the IR and visible spectrums. The IR camera used was a SC 6000 from FLIR Systems, Inc. The HSV system was a Phantom v7.1 from Vision Research.

As configured in this study, the IR camera and HSV system had spatial resolutions of 100 µm and 50 µm respectively. In the case of the IR image, this resolution is more than sufficient to capture the temperature history of individual bubble nucleation events at the nucleation sites, as demonstrated by Theofanous et al. (2002).

Through calibration, IR intensity can be converted to temperature. The thinness of the ITO heater guarantees that the IR camera reading from its bottom is an accurate representation of the actual temperature on the top (wet side) of the heater surface. Use of the IR camera (vs. the more traditional approach based on thermocouples embedded at discrete positions in the heater) enables mapping of the complete two-dimensional time-dependent temperature distribution on the heater surface.

The heat flux was increased in discrete steps up to CHF. At each intermediate step the temperature map and visualization were concurrently recorded for 1s.
The test fluid was deionized (DI) water at atmospheric pressure and all experiments took place with the bulk temperature at the saturation temperature of water, $T_{sat} = 100^\circ C$.

**Figure 1:** MIT pool boiling facility

**BUBBLE GROWTH MODEL**

The traditional theory for bubble growth includes a rapid growth phase consisting of an overpressure-driven, inertia-controlled phase followed by a slower thermal diffusion limited phase. Mikic et al (1970) solved this problem with the following result:

$$R^*(t) - R^*(0) = \frac{2}{3} \left( t^* + 1 \right)^{3/2} - \left( t^* \right)^{3/2} - 1 \] \quad (1)$$

where

$$R^* = \frac{R}{B^2} ; \quad t^* = \frac{t}{B^2} ; \quad A = \sqrt{\frac{c_M}{\rho_v h_{fg}}} \frac{\Delta T_{sat}}{T_{sat} \rho_l}$$

$$B = \sqrt{\frac{12}{\pi}} J a^2 \alpha ; \quad J a = \frac{\rho_c C_p \Delta T_{sat}}{\rho_v h_{fg}}$$

where $c_M = \pi/7$ for bubble growth on a wall surface.

More recent bubble growth theory separates the growth of individual bubbles into two distinct time periods as shown in Figure 2: the initial growth stage and the final growth and departure stage. The initial growth stage corresponds to hemispherical bubble growth from the initial nucleation site with a wedge shaped liquid microlayer remaining below the bubble base. The evaporation of this microlayer fuels further bubble growth and extends its radius, $r_c$. The intense evaporation near the nucleating surface is extremely efficient at removing heat and thus drastically cools the area directly below the microlayer region. A dry spot expands from the nucleation site outwards as that portion of the microlayer is depleted. This dry spot is comparatively inefficient at removing heat. Thus the heater surface in contact with the dried area begins to heat up even as the outer portion of the bubble continues cooling the surface via evaporation. At some time, $t_g$, the final growth and departure stage begins where the bubble’s center of mass begins to move upwards as the bubble shape transforms from hemispherical to spherical. This shape change is due to buoyancy force overcoming the inertial and surface tension forces acting on the bubble. As the bubble shape transitions from hemispherical to spherical, there is little growth of the bubble’s effective radius. During this stage, further growth of the microlayer is limited and facilitates a transition to dominant heat transfer from the macrolayer. The macrolayer is traditionally described as the region between the outer edge of the microlayer to the outer edge of the vapor bubble (Das et al, 2006) as in illustration (b) of Figure 2.

**Figure 2:** Bubble dynamics showing micro and macro layers (a) initial hemispherical growth stage; (b) final growth/departure stage (adapted from Zhao et al., 2002)

During the final growth stage, there are three separate divisions below the bubble consisting of the dryout region, microlayer region and the macrolayer region. The dryout region is the area delimited by the retreating triple point line of the microlayer. The outer radius of the microlayer increases during the initial growth period but essentially stops when the bubble begins to grow into a spherical shape. The macrolayer is not present during the initial growth stage, and extends from the microlayer to the bubble diameter during the final growth stage.

Cooper and Lloyd (1969) studied the formation mechanism of the microlayer both theoretically and experimentally, and expressed its initial thickness at time $t$, neglecting the surface tension effect, as:

$$\delta_{mi}^* = 0.8 \sqrt{\nu t} = \sqrt{c \alpha t}, \quad 0 \leq t \leq t_g \quad (2)$$

where $c=0.64 Pr$.

From this equation, the bubble radius for the initial growth period may be evaluated as:
Once the initial growth period ends, the bubble front has reached the radius, \( r_n \), where the final growth and departure period begins. The bubble radius at the end of this phase can be evaluated as

\[
R = r_c = \frac{2k_i \Delta T_{\text{sat}}}{\rho_r h_{fg} \sqrt{\alpha}} t_g^{1/2}, \quad 0 \leq t \leq t_g . \tag{3}
\]

As the liquid microlayer evaporates, a dryout region forms which can be obtained by considering the change of thickness of the microlayer with time. The radius of the dryout area (\( \delta_{\text{mi}} = 0 \)) is given by (Zhao et al., 2002):

\[
r_d(t) = \left[ \frac{8C_p \rho_l^2 k_i^2 \Delta T_{\text{sat}}^2}{c^2 \alpha h_{fg}^2 \rho_r^2} (t - t_g)^{1/2} \right] . \tag{5}
\]

**EXPERIMENTAL RESULTS**

At low heat flux nucleate boiling, where isolated bubble growth occurs, the growth cycle can be described as follows (Hsu & Graham, 1986). Once the liquid layer above the heater surface reaches the required surface superheat, \( \Delta T_{\text{sat}} \), to activate a given nucleation site a bubble begins to form which pushes the surrounding liquid outward. Evaporation occurs at the bubble interface and through the microlayer, which fuels further bubble growth.

A boiling curve is included in Figure 3 for the experimental run that is discussed in this work. This is generated by taking the average temperature for a \(~5x5\text{mm}^2\) area in the center of the heater across a set (~1s) of IR images for each heat flux shown. The boiling curve shows that the average heater wall temperature compares well with Rohsenhow’s (1952) prediction (\( \Delta T = 9K \)). The Mikic solution seems to work well in the beginning portion of growth, but overpredicts the bubble radius at long time (>6ms). This

A single bubble cycle is chosen from the synchronized experiments and the HSV and IR for this bubble are shown in Figure 4 and Figure 5 respectively. The HSV shown in Figure 5 visually depicts this bubble growth. The depth of field for this particular camera setup is sufficient to see several millimeters past the heater surface, thus capturing the shape and size of the bubble even as it detaches from the heater surface. The outer radius of the bubble, \( R_n \), and the microlayer radius, \( r_c \), are clearly visible in these images. Both the hemispherical radius and dry out radius are assumed from the IR data as shown in Figure 6. The hemispherical radius is taken to be the cooled (thus dark colored) circular expanding area. The dry out area is taken to be the hotter (thus light colored) circular area that expands in the center of the cooled area.

After bubble departure (~ frame 55), cool liquid rushes in to replace the space previously occupied by the bubble. The layer of liquid that is now immediately above the heater surface is gradually heated by transient conduction until it again reaches the required superheat to spawn a new bubble after which the bubble growth process repeats. The time between bubble departure and new bubble growth is called the waiting period, \( t_w \).

Initial hemispherical growth is supported with the HSV of Figure 5. Frame 48 shows that the outer bubble radius, \( R_n \), and the hemispherical radius, \( r_c \), have approximately the same value. Contrast this with later frames (49-51), where the outer bubble radius is significantly larger than the hemispherical radius.

Expansion of bubble radius, \( R_n \), hemispherical radius, \( r_c \), and dry out radius, \( r_d \) for the lifetime of a single bubble at \( q'' = 60\text{ kW/m}^2 \) is shown in Figure 7. These data points are found by enlarging the images with image processing software, and counting the pixels of light/dark areas. The pixel count is then converted to distance by calibration with a scale placed near the region of interest. There is some uncertainty in these measurements, on the order of the camera resolution (100\( \mu \text{m} \)). The growth time, \( t_g \), and departure time can be found using the IR and HSV data respectively. The growth time corresponds to a time where the cooled region stops growing as the bubble transitions from hemispherical to spherical growth and the microlayer has reached its largest radius (frame 50 of Figure 6). The departure time can be seen using the HSV as the time the bubble peels off the heater surface (frame 55 of Figure 5).

The spatial variation of heater temperature across this cold spot is shown in Figure 8. This figure shows temperature data from bubble initiation through bubble departure (~19 ms) and through the wait period where the liquid above the heater surface is gradually heated to the required superheat for subsequent bubble growth. In this data, there is a drastic change in slope of the temperature profile at the three-phase contact line and at the outer edge of the hemispherical radius which makes distance determination straightforward. Initial growth of the bubble, and thus its cooling behavior, is quite symmetric. Late-phase growth and departure can be non-symmetrical, however, as the convection and buoyancy forces affect bubble behavior. This can be seen in the temperature profile at 8 ms.

The Mikic solution of Equation (1) is used to compare the HSV bubble radius data as shown in Figure 7 using a wall superheat taken from the IR data as the average temperature at the individual nucleation site just prior to nucleation, \( \Delta T_{\text{sat}} = 9K \). The Mikic solution seems to work well in the beginning portion of growth, but overpredicts the bubble radius at long time (>6ms).
could possibly be due to the Mikic solution not capturing the physical situation of the bubble shape transitioning from hemispherical growth to spherical as the bubble pulls away from the surface.

The Cooper & Lloyd model for hemispherical bubble growth of Equation (3) is used to compare the IR cold spot radius data as shown in Figure 7. This model works well in the early stage of hemispherical growth for which it is valid.

The Zhao et al. model of Equation (5) is used to compare the IR hot spot radius data as shown in Figure 7. The agreement here is quite good, thus supporting that this hot spot corresponds directly to the movement of the three-phase contact line or dry spot radius.

The growth of cold spot and hot spot are shown for several different bubbles in Figure 9. There is some variation, as expected, but the overall behavior is quite similar between bubbles, and the agreement with microlayer prediction is quite good.

CONCLUDING REMARKS

Novel experimental nucleate boiling data is presented. High speed video and infrared imaging data correspond well with the microlayer model for nucleate boiling as found in available literature. Experimental data from individual bubble growth suggest there is a microlayer of liquid formed underneath initial hemispherical bubble formations. This microlayer proceeds to evaporate and project the three-phase contact line radially outward.

Further experimental investigation and modeling of bubble and dryspot growth are needed, especially at high heat flux. Eventual incorporation of this new data into CHF models for better predictability, especially for novel engineered heat transfer fluids, is desired.

![Figure 3: Boiling curve for DI water generated from IR data (08_002)](image)

![Figure 4: IR data for a single frame showing temperature for the entire heated surface in DI water at 100kW/m². Light areas are warm (~109 °C), and dark areas are cooler nucleation sites)](image)
Figure 5: HSV for a single bubble life-cycle for frames 46-55 in DI water at 60kW/m². Time interval between consecutive images is ~2.08ms (08_002).

Figure 6: IR data for a single bubble life-cycle for frames 46-55 in DI water at 60kW/m². Time interval between consecutive images is ~2.08ms (08_002).
Figure 7: Comparison of bubble, cold spot and dry spot radius with corresponding predictions for DI water at $q''=60kW/m^2$ (08_002).

Figure 8: Temperature evolution across a single cold spot at $q''=60kW/m^2$ in DI water (08_002).

Figure 9: Comparison of cold spot and hot spot radii growth for 5 bubbles with corresponding predictions for DI water at $q''=60kW/m^2$ (08_002).

NOMENCLATURE

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<td>$C_{pl}$</td>
<td>liquid heat capacity (J (kg K)$^{-1}$)</td>
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<td>$C_{sf}$</td>
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Greek symbols

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<td>$\Delta T_{sat}$</td>
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Subscripts

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