Study of bubble growth in water pool boiling through synchronized, infrared thermometry and high-speed video

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Study of Bubble Growth in Water Pool Boiling Through Synchronized, Infrared Thermometry and High-Speed Video

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Abstract
High-speed video and infrared thermometry were used to obtain time- and space-resolved information on bubble nucleation and heat transfer in pool boiling of water. The bubble departure diameter and frequency, growth and wait times, and nucleation site density were directly measured for a thin, electrically-heated, indium-tin-oxide surface, laid on a sapphire substrate. These data are very valuable for validation of two-phase flow and heat transfer models, including computational fluid dynamics with interface tracking methods. Here, detailed experimental bubble-growth data from individual nucleation sites were used to evaluate simple, commonly-used, but poorly-validated, bubble-growth and nucleate-boiling heat-transfer models. The agreement between the data and the models was found to be reasonably good. Also, the heat flux partitioning model, to which our data on nucleation site density, bubble departure diameter and frequency were directly fed, suggests that transient conduction following bubble departure is the dominant contribution to nucleate boiling heat transfer.

Keywords: bubble nucleation, nucleate boiling heat transfer, computational fluid dynamics, interface tracking methods
Nomenclature

A  area (m$^2$)

\( \alpha \)  thermal diffusivity (m$^2$/s)

c  specific heat (J/kg-K)

\( C_{sf} \)  Rohsenhow constant (dimensionless)

d  diameter (m)

\( D_b \)  bubble departure diameter (m)

\( f_b \)  bubble departure frequency (Hz)

h  heat transfer coefficient (W/m$^2$-K)

\( h_{fg} \)  latent heat of evaporation (J/kg)

k  thermal conductivity (W/m-K)

NSD  nucleation site density (#sites/cm$^2$)

\( N_T \)  total number nucleation sites (#)

P  pressure (atm)

\( q'' \)  heat flux (W/m$^2$)

\( \rho \)  density (kg/m$^3$)

\( r_c \)  radius of microlayer (m)

\( r_d \)  radius of dryout region (m)

\( R_{evap} \)  equivalent bubble radius (m)

\( R_t \)  radius of bubble (m)

T  temperature (°C)

t  time (s)

x, y  spatial coordinates on the heater surface (m)

Greek symbols
\( \alpha \)     thermal diffusivity (m\(^2\)/s)
\( \rho \)     density (kg/m\(^3\))
\( \Delta Ts \)   surface superheat (°C)

**Subscript**

bulk     bulk fluid
c      convection partitioned
cycle     bubble cycle
e    latent heat partitioned
evap    evaporation
g    growth
heated    bubble footprint
l    liquid
n    nucleation site number
q    quench partitioned
sat    saturated
tot    total
turb    turbulent natural convection
v    vapor
w    wait or wall
1. Introduction:

Nucleate boiling is an effective mode of heat transfer; and one of the most studied physical phenomena in science and engineering. At low heat flux, where isolated bubble growth occurs, the growth cycle can be qualitatively described as follows (Hsu & Graham [1]). Once the liquid layer above the heater surface reaches the required superheat, $\Delta T_s$, to activate a given nucleation site, a bubble begins to form and pushes the surrounding liquid outward, except for a thin liquid microlayer that remains in contact with the wall underneath the bubble. Evaporation occurs at the bubble surface and through the microlayer, thus fueling further bubble growth. When the size of the bubble is sufficiently large, buoyancy causes the bubble to detach from the surface; new fresh liquid floods the surface, and the cycle restarts.

For decades, nucleate boiling heat transfer has been predominantly an empirical science, accompanied by relatively simple models based on hypotheses that are not always fully justified. For example, the widely popular Rohsenow’s correlation for nucleate boiling is based on the assumption that single-phase convection and nucleate boiling are analogous physical processes, and can be both correlated in terms of the Reynolds and Prandtl number of the liquid phase; for nucleate boiling the characteristic velocity and length are assumed to be the downward liquid velocity and the most unstable Taylor wavelength, respectively; then, an empirical constant, $C_{sf}$, is determined to fit the experimental data for any fluid/surface combination (Rohsenhow [2]).

As researchers are now finally moving away from the rough empiricism of the past, and start to develop more mechanistic models of nucleate boiling heat transfer, the need for high-quality high-resolution data on the bubble nucleation and growth cycle is increasing. Specifically, nucleation site density, bubble departure diameter and frequency data are a necessary input for the source terms in interfacial area transport models (e.g. Ishii & Hibiki [3]) and CFD ‘multi-fluid’ models (e.g. Lo [4]; Bestion et al. [5]; W.K. In & T.H. Chun [6]), as well as semi-empirical models for boiling heat transfer, such as the heat flux partitioning model of Kurul and Podowski [7], Kolev’s bubble interaction model [8] or the more recent hybrid numerical-empirical model of Sanna et al. [9]. Furthermore,
time-resolved temperature distribution data for the boiling surface and direct visualization of the bubble cycle are needed for validation of ‘first principle’ models of bubble nucleation and growth, based on interface tracking methods, in which the geometry of the vapor/liquid interface is not assumed, but rather calculated from a marker function advected according to the Navier-Stokes equations (e.g., Dhir [10], Tryggvason et al. [11], and Stephan & Kunkelmann [12]).

However, gathering the detailed data needed for validation of advanced simulation models is not straightforward. The traditional approaches based on thermocouples and high-speed visualization of the boiling process suffer from several shortcomings; for example, the thermocouples can only measure temperature at discrete locations on the boiling surface, thus no information on the temperature distribution about a nucleation site can be obtained. Further, thermocouples (including micro-thermocouples) have relatively long response time, thus are unsuitable for studying the bubble nucleation and growth phenomena, which have time scales of the order of milliseconds. The usefulness of high-speed video is typically limited by poor optical access to the nucleation site and interference from adjacent bubbles. Second-generation two-phase flow diagnostics, such as multi-sensor conductivity and optical probes (e.g. Kim et al. [13] and Barrau et al. [14]) and wire-mesh probes (e.g. Prasser et al. [15]), can measure bubble diameter and velocity near the boiling surface. However, these approaches are intrusive, and also produce data only at discrete locations within the boiling fluid. It was not until the early 2000s that new possibilities for generating time-resolved multi-dimensional data on the bubble nucleation and growth cycle have opened up with the introduction of infrared-based visualization of thermal patterns on the boiling surface by Theofanous et al. [16].

(ADD MICROHEATERS APPROACH BY JUNGHO KIM)

In this paper we present an approach based on synchronized infrared thermometry and high-speed video through a transparent heater that enables simultaneous measurement of the nucleation site density, bubble growth rate (including bubble departure diameter),
bubble departure frequency (including wait time), and time-resolved 2D temperature distribution on the boiling surface.

The experimental facility used in this research is described in Section 2, the data reduction methodology in Section 3, and the results for bubble nucleation and growth and nucleate boiling heat transfer in Sections 4.1 and 4.2, respectively.

2. Pool boiling facility

The experiments were conducted in the facility shown in Figure 1. A thin film made of Indium-Tin-Oxide (ITO) was electrically heated. ITO is composed of 90% In$_2$O$_3$ and 10% SnO$_2$ by weight. Boiling occurred on the upward facing side of this film which had an exposed area of 30x10 mm$^2$, 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 maintain a constant test-fluid temperature by minimizing heat losses to the ambient. The test fluid was saturated deionized water boiling at P=1 atm (T$_{bulk}$=T$_{sat}$=100°C). Prior to each test, the water was maintained at saturation and the heater was maintained at low heat flux (just below the onset of nucleate boiling) for approximately 30 min to degas the system.

Acquisition of the temperature distribution on the heater surface was accomplished using an infrared (IR) high-speed camera, SC 6000 from FLIR Systems, Inc. The use of an IR camera to investigate boiling heat transfer was pioneered by Theofanous et al. [16]. However, in our system simultaneous high-speed video (HSV) was taken with a high-speed digital imaging system, Phantom v7.1 from Vision Research. A function generator produced a transistor-transistor logic (TTL) pulse which triggered both cameras to simultaneously record an image allowing the synchronization of both cameras’ image sequences. A custom hybrid hot mirror (dichroic) 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 that passes through the hybrid hot mirror 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 IR and visible light.

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 since the typical bubble diameter is on the order of 1000 μm. The frame rate of both cameras was 500 Hz.

While the sapphire substrate is transparent (>85%) to IR light, the ITO has the advantageous property of being opaque in the IR range, as this ensures that all temperature measurements are made on the back (bottom) of the ITO substrate. 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. Thus, neither the temperature of the fluid, nor the integral temperature through the substrate thickness is measured. This makes thermal analysis of the heater, and corresponding temperature measurements straightforward. 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. Heat loss from the heater bottom via air natural convection was calculated to be negligible (<1%).

During each experiment, the heat flux was increased in discrete steps up to the critical heat flux (CHF). At each intermediate step the temperature map and visualization were concurrently recorded for 1.0 sec. Since the typical time scale for a bubble nucleation cycle is tens of ms, 1 sec is sufficient to obtain good data statistics. The interval between heat flux increase and temperature map recording was approximately 4 minutes to ensure that steady state had been reached. Both thermocouples attached to the heater element and the infrared camera where used during scoping experiments to verify that steady state was reached in well under 1 minute.
2.1 Heater surface characterization

As boiling heat transfer is strongly affected by the physico-chemical properties of the heater surface (i.e., roughness, wettability, micro-cavity size and distribution, etc.), extra care was taken in characterizing such properties for the heaters used in the experiments. Both scanning electron microscopy (SEM) and confocal microscopy were used to analyze the heating elements after the experiments to show that there was little modification of the surface after boiling in de-ionized (DI) water. The surface of an ITO heater after boiling in DI water is shown in Figure 2a: the ‘flat’ appearance of the SEM image eloquently confirms that the heater surface is very smooth, and remains smooth and clean after boiling. The surface roughness of the water-boiled heater was SRa=132 nm, as measured by confocal microscopy (Figure 2b), higher than the as-received heater (SRa=30 nm), but still low relative to typical engineering materials. The value of the static contact angle, θ, for an as-received heater was approximately 100°, while the contact angle of the heaters that were boiled in DI water were 80-90°, suggesting that the boiling process alters the surface energy of the heater. The contact angle measurement error was within ±3°.

3. Data reduction and uncertainty

The raw data obtained for each heat flux are in the form of hundreds of frames, each representing a two-dimensional infrared intensity distribution on the heater surface (see Figure 3). The conversion from IR intensity to temperature is done via a calibration curve, obtained using vendor-supplied blackbody simulators; with an accuracy of about 2%, or 2°C. The nucleation sites appear as short-lived dark (cold) spots on the IR image. The edge of the nucleation sites is sharp because there is very little radial conduction within the heater, as discussed above. The nucleation sites in each frame are marked manually; then the nucleation site density can be determined simply as the total number of nucleation sites divided by the area of the heater. The bubble departure diameter is measured from the maximum size of the cold spot. Note that here the bubble diameter is actually the thermal foot-print of the bubble, i.e., the bottom of the bubble that is in contact with the heater surface. The actual bubble departure size is typically larger and
can be measured with the HSV. If only the infrared data along a chord cutting through a nucleation site are considered, the one-dimensional temperature distribution vs. time of Figure 4 is obtained. Further, if the spatial average of the temperature at a given nucleation site is calculated and plotted vs. time, then various features of the bubble cycle, such as the bubble departure frequency, bubble growth time and bubble wait time become apparent and can be readily estimated (see Figure 5). Since boiling is essentially a random phenomenon, for each nucleation site, there is a distribution of the parameters; however, we observed that the parameters tend to be distributed normally and narrowly about their mean.

The uncertainties in measuring the bubble radius (with the HSV images) and the cold spot and hotspot radii (with the IR images) stem from two factors: accuracy of the distance calibration converting pixel size into distance units, and measurement bias (since the measurement is done manually by looking at the contrast between the liquid/vapor interface, the measurement could be off by 1-2 pixels. The combination of these two factors results in an estimate for the total uncertainty in the bubble radii to be approximately 10%.

The uncertainty in measuring the nucleation site density is expected to be small, since each frame is examined manually to determine the nucleation sites. Two counting runs were done for the same set of images with a high number of nucleation sites, with the difference between the two counts being only 1-2 nucleation sites. Thus, the total uncertainty in the nucleation site density measurement was estimated to be well under 2%.

The growth, wait, and cycle time measurements were automatically determined using the temperature history of an individual nucleation site. The algorithm picks the times where the slope of the temperature history changes with no uncertainty; that information is then used to determine the frequencies. This was confirmed by comparing manual examinations of select temperature histories with the algorithm. The uncertainty in measurement of the initiation and completion of bubble growth for an individual bubble
cycle could be as large as the time between individual frames (2 ms). However, a large number of repeated nucleation cycles for an individual nucleation site are used to generate the mean times for that site, so the reported mean growth, wait and cycle times should reflect the true times well (±20%).

The heat flux is estimated from measurement of the voltage and current (both with very low uncertainties, less <1%) and knowledge of the heater surface area. Therefore, the uncertainty in the heat flux measurement is estimated to be less than 1%.

In the remainder of the paper we will use only the mean values for all these parameters, but the associated uncertainties should be kept in mind.

We shall note, in passing, that surface temperature data of the type shown in Figure 4 could prove extremely valuable for validation of numerical models of boiling, as more and more researchers are attempting CFD simulations of the bubble nucleation process ([10], [11], [12]). In these models the conjugate heat transfer problem for the heater must be solved for, along with the evaporation phenomena in the liquid, so comparing the calculated and measured temperature distribution on the heater surface is a means to validate the model.

4. Experimental results
Boiling curves for the various experimental runs discussed in this paper are shown in Figure 6. The critical heat flux (CHF) consistently occurred between 900 and 1000 kW/m². In our experiments CHF was always accompanied by a large sudden excursion of the heater surface temperature resulting in physical burnout of the heater. The boiling curves are generated by taking the average temperature for a ~5x5 mm² area in the center of the heater across a set of IR images for each heat flux shown. Comparison of the experimental boiling curves to the predictions of the Rohsenow’s [2] correlation for nucleate boiling (Cₜ=0.010 [17]), Zuber’s [18] correlation for critical heat flux (CHF), and the Fishenden & Saunders’s correlation [19] for natural convection, suggests that in spite of the uncommon heater design, our boiling tests are fairly typical.
IR and HSV data from these runs were used for detailed analysis of the bubble growth cycle (Section 4.1) and nucleate boiling heat transfer (Section 4.2).

4.1 Bubble nucleation and growth

A single representative bubble cycle is chosen from the synchronized experiments and the HSV and IR for this bubble are shown in Figure 7. The HSV shown in Figure 7(a) visually depicts 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. To interpret these data, it is useful to refer to the commonly accepted model for bubble growth at a boiling surface, which is shown in Figure 8. The actual outer radius of the bubble, $R_t$, and the microlayer (hemispherical) radius, $r_c$, are clearly visible in the images of Figure 7(a). Both the microlayer radius and dry spot radius are measured using the IR images as shown in Figure 7(b). The microlayer 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 as the microlayer evaporates in the center of the cooled circular 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 nucleation is the wait period, $t_w$.

Initial hemispherical growth is confirmed by the HSV of Figure 7(a). Specifically, frame 48 shows that the outer bubble radius, $R_t$, and the hemispherical microlayer radius, $r_c$, have approximately the same value, suggesting that the initial bubble growth is primarily in the radial direction along the surface. Contrast this with later frames (49-51), where the outer bubble radius is significantly larger than the hemispherical radius. Zhao et al. [20] developed an expression for the radius of the dryout area as a function of bubble growth time which expanded upon the theoretical and experimental analysis of
microlayer growth by Cooper and Lloyd [21]. The Cooper and Loyd [21] expression for the hemispherical bubble radius and the Zhao et al. [20] expression for microlayer dryout radius are compared with the cold spot and hot spot radii as measured using the infrared camera for q”=60kW/m² in Figure 9. Data for five bubbles from the same experiment were considered in order to show a clearer picture of bubble growth variability. The average radii values are represented by the data point, while the error bars represent the minimum and maximum radii of the five bubbles considered. Measurement error is ±10%, as discussed in Section 3. There is some disparity between different bubbles, as expected, but the overall behavior is consistent across the evaluated bubbles, and the agreement with the microlayer prediction is reasonable. The existence of a centrally expanding hot spot in the IR images, and the bubble growth analysis confirms the existence of microlayer evaporation during nucleate boiling in water through the direct measurement of surface temperature during bubble growth. A previous study by Koffman and Plesset [22] used laser interferometry to record microlayer evaporation, but had a large amount of uncertainty due to the measurement technique (e.g. interpretation of fringe patterns). The technique based on synchronized IR thermography and HSV is shown here to be an effective method of directly measuring the movement of the three-phase contact line during microlayer evaporation.

These results are significant because they confirm that: (i) there is a microlayer of liquid formed underneath initial hemispherical bubble formations, and (ii) this microlayer proceeds to evaporate and project the three-phase contact line radially outward. However, further experimental investigation and modeling of bubble and dryspot growth are needed, especially at high heat flux.

The data were also used to probe the heat transfer mechanisms responsible for bubble growth, as follows. Assuming that all heat transferred from the wall is used as latent heat, an equivalent bubble radius, R_{evap}, can be computed as:

$$\rho_v \frac{4\pi}{3} r_{evap}^3(t) h_f = \int_0^t \int_{A(t)} q''(x,y,t) dx dy \tag{1}$$

or:
\[ r_{\text{evap}}(t) = \left( \frac{3}{4\pi} \int_0^t \frac{A(t)}{\rho v h_{fg}} dt \int q''(x, y, t) dx dy \right)^{1/3} \]  

(2)

With \( x \) and \( y \) being the spatial coordinates on the surface, and \( A(t) \) the footprint of the bubble at any time, \( t \), taken from the measured bubble radius using the HSV data. The instantaneous local value of the heat flux, \( q''(x, y, t) \), is determined from solving the heat conduction equation \( (\rho c \frac{\partial T}{\partial t} = k \nabla^2 T) \) in the sapphire substrate with the IR-measured temperature distribution on the surface, \( T_A(x, y, t) \), as the boundary condition. An adiabatic boundary condition was used for the bottom of the sapphire substrate. In Figure 10, the measured bubble radius in DI water from the HSV is compared to the equivalent radius computed by Eq. 2 for a nominal heat flux of 50 kW/m\(^2\). The figure shows that the computed equivalent radius is close to the measured radius, thus suggesting that the bubble gains a significant amount of the energy required for its growth from direct heat transfer from the wall. This finding is consistent with models such as Dhir and Liaw’s [26] and Zhao et al.’s [20], which hypothesize evaporation of the microlayer at the wall to be the dominant mechanism of heat transfer during fully developed nucleate boiling, and also the experiments by Stephan et al. [27] who determined that approximately 50-60% of the latent heat fueling bubble growth flows through the microlayer region. On the other hand, the FC-72 experiments by Yaddanapudi and Kim [23] and Demiray and Kim [24], [25] suggest that most heat for bubble growth comes from the superheated liquid layer around the bubble. Likely, the relative importance of the two energy sources (wall/microlayer vs superheated liquid layer around the bubble) depends on the fluid, surface, and heat flux, so no definitive conclusions on the bubble growth mechanisms can be drawn at this time.

4.2 Nucleate boiling heat transfer

To study nucleate boiling heat transfer, the key bubble parameters (\( D_b, \ \text{NSD}, \ f_b, \ t_g, \ t_w \)) discussed in Section 3 were collected for each nucleation site at each heat flux in each test run, and then used in the popular heat flux partitioning model (Kurul & Podowski, [7]), which has also been labeled as the “RPI Model” after Kurul and Podowski’s
The model is based on the Bowring scheme of accounting for the various boiling heat transfer mechanisms separately. Both were primarily developed for flow boiling, but have been extended and applied to pool boiling here.

The heat removed by the boiling fluid is assumed to be through the following contributions:

1. the latent heat of evaporation to form the bubbles \(q''_e\)
2. heat expended in re-formation of the thermal boundary layer following bubble departure, or the so-called quenching heat flux \(q''_q\)
3. heat transferred to the liquid phase outside the zone of influence of the bubbles by convection \(q''_c\).

The total boiling heat flux is obtained through the addition of the three fluxes as:

\[
q_{\text{tot}} = q''_e + q''_q + q''_c
\]

(3)

Since the present work has obtained detailed information for the bubble parameters, it is possible to write expressions for the partitioned heat fluxes that incorporate the contributions of each nucleation site. The latent heat flux can be written as:

\[
q''_e = \frac{\pi}{6A} \rho_f h_{fg} \sum_{n=1}^{N_T} \left( f_{b,n} \cdot D_{b,n}^3 \right)
\]

(4)

where \(N_T\) is the total number of nucleation sites. The Han and Griffith assumption was used in the analysis of conductive heat transfer to the liquid in between bubble growth. They assume that as a bubble departs, it carries an area of the superheated thermal boundary layer with it in its wake equal to twice the bubble diameter. Then, the cool liquid that rushes in to replace it is heated via transient conduction from the heater, thus the total quench heat flux is given as:

\[
q''_q = \frac{2\pi k_i (T_u - T_{sat})}{A \sqrt{\pi \alpha_i}} \sum_{n=1}^{N_T} \left( D_{b,n}^3 \left( T_{u,n} f_{b,n} \right) \right)
\]

(5)
The McAdams [30] estimate for the turbulent free convection heat transfer coefficient from a flat upwards-facing plate is used to estimate the convection heat flux as:

\[
q_c = \left[1 - \frac{\pi}{4\,A} \sum_{n=1}^{N_r} \left(D_{h,n}\right)^2 \right] h_{\text{turb}} \left(T_w - T_{\text{sat}} \right)
\]  

(6)

The boiling curve for one test run is shown in Figure 11 along with the evaporation, quench, convection and total partitioned heat fluxes that have been calculated using the method described above. The model works surprisingly well when considering the amount of independent data that has been fed into it. It is also interesting to note that the quench heat flux is the dominant partitioned heat flux, and not the latent heat flux, as one may expect.

5. Conclusions:
Synchronized high-speed video and infrared thermometry were used to obtain time- and space-resolved information on bubble nucleation and boiling heat transfer. This approach provides a detailed and systematic method for investigating the fundamentals of nucleate boiling. Data on bubble departure diameter and frequency, growth and wait times, and nucleation site density can be effortlessly measured for all nucleation sites on the heater surface. The main findings of the study are as follows:

- Time-resolved data for bubble radius, microlayer radius and dryout radius were compared to decades-old and poorly validated models and correlations. The agreement between the data and the models is (surprisingly) reasonable.

- The RPI heat flux partitioning model, to which our data on nucleation site density, bubble departure diameter and frequency were directly fed, suggests that the quench heat flux (i.e., the transient conduction heat transfer following bubble departure) is the dominant contribution to nucleate boiling heat transfer.

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References


Figure Captions

Figure 1: MIT pool boiling facility with infrared thermometry and high-speed video cameras.

Figure 2: SEM image of ITO heater boiled in DI water; 5000x magnification in the center of heater.

Figure 3: Sample screenshot of selecting the diameter of a nucleation site (yellow line bisects diameter). Nucleation sites appear as dark (cold) spots in IR images.

Figure 4: 1D temperature distribution on the heater surface underneath a growing bubble.

Figure 5: Temperature response below individual nucleation site showing frequency response of nucleation cycle. Average temperature of entire nucleation site is used. Note the characteristic slow heating and sudden cooling cycles, which are expected during a bubble nucleation event. $t_{cycle}$ is the sum of the growth time, $t_g$, and wait time, $t_w$. The average value of the cycle times can be used to find the characteristic bubble departure frequency ($f_b=1/t_{cycle}$).

Figure 6: Boiling curve for DI water. Experimental results are compared with several models.

Figure 7: (a) High speed video (HSV) and (b) infrared (IR) temperature data for a single bubble life-cycle. Frames 46-55 are shown for DI water at $q''=60$ kW/m², with the time interval between consecutive images being ~2.08ms. Bubble incipience is seen in frame 47 on the HSV, end of bubble growth in frame 51 and complete bubble departure at frame 55. The IR data show the bubble thermal footprint growing in frames 48-51, and a central expanding “hot” region corresponding to the evaporation of the microlayer and growth of the dryout region.

Figure 8: Schematic of a growing bubble and related heat transfer mechanisms.

Figure 9: Comparison of cold spot and hot spot radii growth for 5 bubbles with corresponding predictions for DI water at $q''=60$ kW/m². Error bars represent minimum and maximum measured values in order to show experimental spread. Measurement error ±10%.

Figure 10: Comparison of the measured radius, $R_i$, (taken from HSV) to the equivalent radius, $R_{evap}$, $\frac{q''}{15} = 50$ kW/m² in DI water. Error bars represent minimum and maximum
measured/calculated values in order to show experimental spread. Measurement error ±10%.

Figure 11: Comparison of actual boiling curve (●) with RPI partitioning model using corresponding bubble parameters (D_b, NSD, f_b, t_g, t_w) at each superheat for a single DI water test. The uncertainty on the measured values of the heat flux is ~1%.
Figure 1: MIT pool boiling facility with infrared thermometry and high-speed video cameras.
Figure 2: (a) SEM and (b) Confocal Microscopy images of ITO heater boiled in DI water. SEM image is at 5000x magnification in the center of heater. The picture is featureless (nearly entirely grey) showing that the nano-smooth heater has not been modified by boiling in water. The confocal microscopy image at 50x magnification confirms that the maximum feature size is \( \sim 130 \) nm.
Figure 3: Sample screenshot of selecting the diameter of a nucleation site (yellow line bisects diameter). Nucleation sites appear as dark (cold) spots in IR images.
Figure 4. 1D temperature distribution on the heater surface underneath a growing bubble.
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