Transient boiling of water under exponentially escalating heat inputs. Part I: Pool boiling

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Transient boiling of water under exponentially escalating heat inputs

Part I: Pool boiling

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ABSTRACT

This paper presents an investigation of transient pool boiling heat transfer phenomena in water at atmospheric pressure under exponentially escalating heat fluxes on plate-type heaters. Exponential power escalations with periods ranging from 5 to 100 milliseconds, and subcooling of 0, 25 and 75 K were explored. What makes this study unique is the use of synchronized state-of-the-art diagnostics such as InfraRed (IR) thermometry and High-Speed Video HSV, which enabled accurate measurements and provided new and unique insight into the transient boiling heat transfer phenomena. The onset of nucleate boiling (ONB) conditions were identified. The experimental data suggest that ONB temperature and heat flux increase monotonically with decreasing period and increasing subcooling, in accordance with the predictions of a model based on transient conduction and the nucleation site activation criterion. Various boiling regimes were observed during the transition from ONB to fully developed nucleate boiling (FDNB). Onset of the boiling driven (OBD) heat transfer regime and overshoot (OV) conditions were identified, depending on the period of the power escalation and the subcooling. Forced convection effects have also been investigated and are discussed in the companion paper (Part II).

Keywords

Exponential power escalation
Heat transfer mechanisms
Infrared thermometry
High speed video
Transient Boiling

1. Introduction

Transient boiling heat transfer is important to the safety of nuclear reactors. Step inputs of reactivity in a nuclear reactor might result in a power excursion in which the heat generation in the nuclear fuel rises exponentially with time $q''(t) \propto e^{t/\tau}$. The period of the exponential power excursion $\tau$ depends upon the size of the reactivity step. Large steps yield to periods that can be as short as a few milliseconds. The heat generated within the fuel is transferred to the water coolant which then starts to boil. The reactivity feedbacks caused by the heating (Doppler in the fuel and void in the coolant) represent an important mitigation mechanism for such accidents. Depending on the magnitude and the delay of these feedbacks, a safe conclusion to the accident is rapidly achieved or, in extreme cases, the fuel can melt, the molten material can be expelled, fragmented and possibly lead to
steam explosion. The time delay between heat generation within the fuel and its transfer to the coolant is key to determining the outcome of the accident, in particular for experimental reactors using highly enriched fissile fuel with a very low Doppler effect. This time delay depends on conduction heat transfer within the fuel, single-phase convective heat transfer and eventually transient boiling heat transfer in the coolant.

Transient boiling of water under exponentially escalating heat fluxes has been studied since the 1950s. Most of these investigations were carried out in pool boiling conditions, using ribbon [1, 2] and wire [3, 4, 5, 6, 7] heaters. Some forced convection studies also exist for ribbon [8] and wire [9] heaters. Table 1 summarizes the experimental conditions and diagnostics of these earlier investigations.

All these studies used the same technique to determine the instantaneous heater average temperature and net heat flux to water. The average heater temperature was determined through measurement of the heater resistance, generally made of Platinum, Aluminum or Deltamax®, whose resistivity changes with temperature. The instantaneous net heat flux to water was determined as the difference between the power released by Joule heating $V(t) \cdot I(t)$ and the rate of change of the energy stored within the heater itself $C_h \cdot dT_h(t)/dt$. For thin heaters with a negligible thermal resistance [1, 2, 8], the average temperature on the boiling surface could be assumed equal to the average heater temperature. For relatively thick heaters [3, 4, 5, 6, 7, 9], the temperature on the boiling surface could be determined by solving the unsteady thermal conduction equation in the heater, having the time dependent generation rate (Joule heating) as source term and the net heat flux to water as boundary condition at the boiling surface.

High speed video (HSV) was used to identify ONB and visualize the boiling process [1, 5, 6, 8]. Piezoelectric hydrophones were used to detect ONB in subcooled conditions [3]. X-ray absorption was used to measure void fractions in transient flow boiling experiments [8].
Table 1. Experimental conditions and diagnostics used in studies of transient boiling heat transfer with exponentially escalating heat inputs.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Year</th>
<th>Boiling conditions</th>
<th>Heater</th>
<th>Subcooling</th>
<th>Periods</th>
<th>Pressures</th>
<th>HSV</th>
<th>ONB detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rosenthal [1]</td>
<td>1957</td>
<td>Pool</td>
<td>Pt and Al ribbon</td>
<td>0 to 68 K</td>
<td>5 to 75 ms</td>
<td>Ambient</td>
<td>6000 fps</td>
<td>Temperature overshoot and HSV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.025 mm thick 2.5 mm wide</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Hall and Harrison [2]</td>
<td>1967</td>
<td>Pool</td>
<td>Pt ribbon</td>
<td>0 to 80 K</td>
<td>0.7 to 5 ms</td>
<td>Ambient</td>
<td></td>
<td>Temperature overshoot</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>0.025 mm thick 2.5 mm wide</td>
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<tr>
<td>Johnson [8]</td>
<td>1971</td>
<td>Stagnant and forced flow</td>
<td>Deltamax® ribbon</td>
<td>5 to 62 K</td>
<td>5 to 50 ms</td>
<td>Ambient to 13.8 MPa</td>
<td>Yes</td>
<td>HSV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.10/0.36 mm thick 3.2 mm wide</td>
<td></td>
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<tr>
<td>Sakurai and Shiotsu [3]</td>
<td>1977</td>
<td>Pool</td>
<td>Pt wire</td>
<td>25 to 75 K</td>
<td>5 ms to 10 s</td>
<td>Ambient</td>
<td></td>
<td>Acoustic detection by piezoelectric hydrophone</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>diameter 1.2 mm</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Sakurai and Shiotsu [4]</td>
<td>1977</td>
<td>Pool</td>
<td>Pt wire</td>
<td>0 K</td>
<td>5 ms to 10 s</td>
<td>Ambient to 2.1 MPa</td>
<td></td>
<td>No ONB detection</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>diameter 1.2 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Kataoka et al. [9]</td>
<td>1983</td>
<td>Forced flow</td>
<td>Pt wire</td>
<td>10 to 70 K</td>
<td>5 ms to 10 s</td>
<td>0.143 to 1.503 MPa</td>
<td></td>
<td>No ONB detection</td>
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<td></td>
<td></td>
<td></td>
<td>diameter 0.8/1.2/1.5 mm</td>
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<tr>
<td>Sakurai et al. [5, 6]</td>
<td>2000</td>
<td>Pool</td>
<td>Pt wire</td>
<td>0 K</td>
<td>2 ms to 20 s</td>
<td>Ambient to 2.063 MPa</td>
<td>200 fps</td>
<td>HSV</td>
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<td></td>
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<td>diameter 1.2 mm</td>
<td></td>
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<tr>
<td>Park et al. [7]</td>
<td>2010</td>
<td>Pool</td>
<td>Pt wire</td>
<td>0 to 160 K</td>
<td>5 ms to 50 s</td>
<td>Ambient to 1.572 MPa</td>
<td></td>
<td>Not discussed</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>diameter 1.0 mm</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>This study</td>
<td>2015</td>
<td>Pool / Flow</td>
<td>ITO/sapphire heater</td>
<td>0 to 75K</td>
<td>5 ms to 500 s</td>
<td>Ambient</td>
<td>5000 fps</td>
<td>HSV and IR thermometry</td>
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In a transient pool boiling test it is typical to identify several characteristic features, i.e. the single-phase heat transfer regime, the onset of nucleate boiling (or boiling inception), the fully developed nucleate boiling regime and ultimately the boiling crisis. A brief summary of the previous work on and current understanding of each of these features is presented next.

### 1.1. Single-phase heat transfer

Transient non-boiling heat transfer is a well understood phenomenon. For short periods, typically smaller than 100 ms, the temperature rise on the heater surface is too fast for natural convection to develop and contribute to heat transfer [1, 2, 3, 10]. Conduction is the leading heat transfer mechanism. Thus, transient conduction equations can be solved to determine the temperature on the heater surface and the temperature distribution in water. For longer periods, the temperature rise on the heater surface is slow. Buoyancy forces set the fluid in motion and natural convection supersedes pure conduction [3].

### 1.2. Onset of nucleate boiling

There is general agreement that the transient ONB superheat decreases with decreasing subcooling and increasing pressure, as implied by the steady boiling inception criteria, i.e. the Hsu’s model [11]. Transient effects are also qualitatively clear. ONB superheat and heat flux decrease as the exponential period is increased. However ONB data reported in the literature are often very scattered and are not free from discrepancies, as explained next.

Rosenthal [1] was the first to identify the ONB conditions using a high-speed camera synchronized with measurements of voltage and current through a ribbon heater. Accordingly, the ONB detected through HSV coincides with a maximum of the heater temperature, which was called overshoot (OV). Rosenthal observed a significant rise in the boiling inception temperature with respect to the steady heat transfer tests, however, for saturation condition, no major differences were observed with respect to steady boiling and surprisingly the superheat was found to be negligible small for periods larger than 70 ms.

Later, Hall and Harrison [2] investigated boiling inception conditions for very short periods (<5 ms). Based on the observation of Rosenthal, they assumed that boiling inception coincides with the overshoot. To predict the ONB superheat, they tried to apply the model proposed by Hsu [11] combined with the transient conduction temperature profile. However, the measured incipient boiling superheats were much higher (~30 K) than the predicted values.

The first to point out the difference between boiling inception and overshoot was likely Johnson [8], who used HSV to image the boiling surface and X-ray absorption to measure the void fraction. According to Johnson, boiling inception occurs at the intersection between the transient non-boiling heat transfer curve and the steady-state fully developed nucleate boiling curve.

In 1977, Sakurai and Shiotsu [3] identified boiling inception conditions at ambient pressure and various subcoolings (25 to 75 K) through a piezoelectric hydrophone synchronized with the measurement of the heater temperature (through the heater resistance). They showed that ONB temperatures are significantly lower than overshoot temperatures, and can be predicted with models developed from the formulations of Hsu [11] and Rohsenow [12]. Tuning of the largest unflooded cavity size was however required to fit the experimental data for each subcooling explored.

In 2000, Sakurai et al. [5, 6] measured the boiling inception superheat for saturation conditions at ambient pressure using HSV (200 fps). In doing so, they discussed the difference between highly wetting fluids and water, both pre-pressurized to flood the cavities, and non-pre-pressurized. In particular, they argued that even for non-pre-pressurized water, for very short period, boiling inception could be triggered by heterogeneous spontaneous nucleation instead of nucleation in active unflooded cavities. Contrary to Rosenthal, they showed that the onset of nucleate boiling temperature can be significantly higher than in steady boiling also for saturation conditions and relatively long periods. Surprisingly, the ONB superheats for saturation conditions reported in this work are higher than superheats previously measured by the same author for subcooled conditions [3].

### 1.3. From ONB to critical heat flux

Rosenthal [1] reported that after ONB the number of bubbles on the surface grows rapidly. These bubbles re-condense and the inrush of cold liquid cools down the surface and hinders further nucleation, until boiling restarts in a fashion similar to steady
boiling. For relatively long period (larger than 15 ms), the behavior of the system was not appreciably different than steady boiling and thus critical heat flux conditions were not influenced by the power excursion period.

A similar description of the transition between non-boiling regime and boiling crisis was reported by Johnson [8]. No major differences with respect to steady boiling were observed for the fully developed nucleate boiling regime for periods of 5 ms or longer. However, measured transient critical heat fluxes were higher than the steady-state values.

Based on the observation of temperature fluctuations after ONB, Hall and Harrison [2] speculated that even at very short periods (< 5 ms) the transition from single-phase heat transfer to the boiling crisis was not instantaneous but was preceded by nucleation of individual bubbles. During this phase the heat flux could exceed the critical heat flux for steady conditions by an order of magnitude. A similar behavior was also observed through HSV by Tachibana et al. [13] for linear power excursions.

Sakurai and Shiotsu [3, 4] confirmed the presence of a large temperature overshoot after boiling inception and postulated the existence of two different boiling processes. The overshoot was explained as the result of the time leg of activation of small cavities and initially flooded cavities for the increasing rate of heat flux [4]. In the quasi-static boiling process (i.e. for relatively long periods), fully developed nucleate boiling is attained shortly after the temperature overshoot. In the rapid boiling process, when the power excursion period is very short, the critical heat flux condition is instead reached before potential active cavities are fully activated. Contrary to Rosenthal, CHF was observed to vary as a function of power excursion period and pressure.

Sakurai found that, for subcooled conditions, CHF increases as the pressure increases and the period decreases, also for relatively long periods (> 5ms) [6]. For saturation conditions the trend is more complicated. Depending on the pressure, the critical heat flux could increase, then decrease and finally increase again as the power excursion period decreases [5, 6]. In particular, at short power excursion periods, when boiling is triggered by heterogeneous spontaneous nucleation (HSN), the transition from ONB to CHF is rapid even for non-pre-pressurized water. Similar trends were observed by Kataoka et al. [9] in transient tests with forced convection and by Park et al. [7].

Although the previous experimental databases form a highly valuable source of information, it must be remarked that sometimes the conclusions of the different authors are quantitatively and qualitatively in disagreement with each other. This is likely due to differences in experimental setups and also limitations in the accuracy of diagnostics available in those experiments. In order to clarify these discrepancies and shed light on the mechanisms of transient boiling heat transfer, this paper and its companion paper [14] present the results of a new experimental program devoted to the study of exponential power excursion in both pool boiling and flow boiling conditions, respectively. In this paper, periods in the range from 5 ms to 100 ms and bulk temperatures from saturation to 75 K of subcooling have been explored at ambient pressure in pool boiling conditions. What makes this study unique is the use of synchronized state-of-the-art diagnostics such as IR thermometry and HSV which can improve the accuracy of measured quantities and provide new and unique insight into the transient boiling heat transfer phenomena.

2. Description of pool boiling facility and diagnostics

The custom designed and built experimental setup used in this study is sketched in Figure 1. It consists of a stainless steel boiling cell surrounded by an isothermal bath, a heater with its cartridge installed at the bottom of the boiling cell, a sampling line to measure dissolved oxygen concentration and a volume compensation system. A high-level 5V signal is used to trigger two function generators (FG1 and FG2) and the high-speed data acquisition system (HDAS). FG1 is used to drive HSV and IR cameras. FG2 is used to drive the high-speed direct current power supply (DCPS, sketched as a battery in Figure 1) in order to output the desired exponential power excursion. The HDAS acquires trigger signal, camera input signal (output of FG1), as well as voltage and current through the heater.
Figure 1. Schematic diagram of experimental setup and diagnostics for pool boiling tests.

2.1. Boiling cell

The pool boiling cell features a concentric-double-cylinder structure made of 316L stainless steel. Boiling of DI water takes place in the inner cell, while the outer enclosure functions as an isothermal bath. The whole facility is surrounded by thermal insulating foam. The temperature (and thus the degree of subcooling) of the water in the inner cell is regulated by circulating a temperature-controlled fluid through the isothermal bath with an accuracy of ±1°C. The heater cartridge sits at the bottom of the cell and accommodates heater samples. There are four glass windows spaced equally at 90° around the outer surface of the boiling cell which are used by the HSV camera for imaging the boiling phenomena on the heater surface.

2.2. Heater

Boiling was induced by a specially-designed heater (see Figure 2) installed in the boiling cell by means of a graphite-macor cartridge. The heater and cartridge were designed to prevent the occurrence of corrosion, which could influence the results. The heater consists of: (i) a 1 mm thick, IR quasi-transparent sapphire substrate, (ii) a 0.7 μm thick, electrically conductive, IR opaque, indium tin oxide (ITO) wrapped-around coating, and (iii) 0.7 μm thick wrapped-around gold pads. The ITO film (boiling surface) has a constant resistivity of approximately 2.5 Ohms/square in the temperature range of interest [15]. It is typically nano-smooth (see Figure 3) and hydrophilic (the contact angle is approximately 85°). However, scanning electron microscope (SEM) investigations revealed the presence of randomly distributed imperfections with typical equivalent diameter in the order of a few microns. The desired power excursion was generated by applying a transient voltage to the ITO coating through the gold pads, using the DCPS. The heat thus generated within the ITO film (active area: 1 cm × 1 cm) is partially transferred to water and partially to the sapphire substrate (see Section 2.5).

Figure 2. Heater schematic drawing (left, not to scale), and picture (right)
2.3. High-speed direct current power supply (DCPS)

A Chroma 62050P-100-100 DCPS generated the desired exponential power escalation. The maximum output power of the DCPS is 5kW, with maximum current and voltage of 100A and 100V respectively. The nominal maximum voltage slew rate is 10V/ms, while the current slew rate follows the voltage variation with respect to the electrical resistance. These high power and high slew rate features enabled exponential heat flux excursions with periods as small as 5ms, with a precision of ± 0.1 ms.

2.4. High-speed data acquisition system (HDAS)

An Agilent U2542A USB modular high speed data acquisition system (HDAS) was adopted to acquire trigger signal, camera input signal (output of FG1), as well as signals of current and voltage through the heater. Current was measured through a shunt, which converts the actual heater current to a voltage signal (50mV/30A) with a manufacturer-specified accuracy of 0.25%. A voltage divider was applied to reduce the actual voltage through the heater (up to 100V) to a range acceptable to the HDAS (0-10V input). In the present study, a sampling rate of 50 kHz (50 samples/ms) for each channel was used. The measuring accuracy for the heater voltage and current were 0.15 mV and 11.4 mA, respectively. The thermal power released by Joule heating per unit area of the ITO was calculated as

\[ q_{tot}'(t) = \frac{V(t) \cdot I(t)}{A_h} \]  

where \( A_h \) is the active area of the ITO film. The size of active area (approximately 1 cm²) was measured by means of the scanning electron microscope. Using this technique, we could safely assume that the uncertainty on the size of the actual active area was smaller than ±1%.

2.5. Infrared (IR) camera and IR thermometry

An IRC-800 high-speed infrared camera was used to record the temperature distribution on the heater surface, equipped with a 100mm germanium lens (f/2.3) and a 1/2” extension ring. The achieved spatial resolution was 115 microns at a frame rate of 2500 fps. An integration time of 200 μs was used. The sensor of the IR camera captures Mid-IR radiation (in the 3-5μm wavelength range) from the ITO heater surface, which was reflected through a gold coated mirror (see Figure 1). The mirror reflectivity is more than 0.99, which ensures the purity of the IR signal after reflection. The camera sensor detects the IR radiation intensity and outputs the signal as counts. Radiation counts depend on the temperature of the boiling surface (ITO film). However, due to the slightly emitting nature of the sapphire substrate between 4.0 and 5.0 microns, the signal emitted by the ITO is partially “contaminated” by the emission of the substrate. Therefore, to achieve an accurate estimate of wall temperature and heat flux in transient conditions, the solution of a coupled 3D conduction/radiation inverse problem was required. A description of this technique is reported in Appendix A. More details can be found in Ref. [16]. The temperature distribution \( T_s(x,y,z_o,t) \) in the sapphire substrate (see Figure 4) and the local heat flux from the ITO heater to sapphire \( q_s''(x,y,t) \) are known through the
solution of this coupled radiation-conduction inverse problem. Then, since the ITO film has negligible thermal resistance and thermal capacity, the local heat flux to water was calculated as

\[ q''_w(x,y,t) = q''_{\text{tot}}(t) - q''_s(x,y,t) = \frac{V(t) \cdot I(t)}{A_h} - q''_s(x,y,t) \]  

(2)

It must be emphasized that accurate synchronization of the camera input, voltage and current signals was essential to estimate with precision the heat flux to water by Eq. (2).

![Figure 4](image.png)

**Figure 4.** Distribution of heat fluxes at the sapphire-ITO-water interface.

### 2.6. High speed Video (HSV)

A Phantom 12.1 high speed video camera (Vision Research) was used for imaging the boiling process. An AF Micro-Nikkor 200mm f/4D lens (Nikon) was mounted on the camera for “close-up” imaging of the boiling area with a spatial resolution of 25 μm. In the present study, a sampling rate of 5,000 fps was applied with exposure time of 90 μs. Such high spatial and temporal resolutions allowed for precise identification of the ONB moment. Combining HSV and IR images, the ONB moment could be identified within an interval of 100 μs.

### 2.7. Dissolved oxygen (DO) control and measurement

To quantify the presence of non-condensable gases and minimize their effect on the onset of nucleate boiling, a system to sample water and measure the dissolved oxygen (DO) concentration was installed on the lid of the boiling cell (see Figure 1). A volume compensation system was also deployed to eliminate the contact between water in the boiling cell and air from the environment, and adjust volume changes maintaining the ambient pressure in the boiling cell. To reduce the concentration of non-condensable gas, the deionized water used in these experiments was vigorously boiled for 1 h. Steady boiling on the test surface was also carried out to eliminate non-condensable gases trapped inside surface cavities (20 mins). The DO concentration of the water sample was monitored with an Extech 407510 DO meter before and after each series of experiments. The DO concentration measured at the operating temperatures was always steady (typically between 2.1 and 2.5 ppm) and much lower than the saturation value (typically around 8.6 ppm at ambient conditions). Combining Young-Laplace equation and Henry’s law, we estimated that, for a DO concentration of 2.5 ppm and cavity diameter of 5 microns, the temperature decrease at ONB would be approximately 0.35 °C with respect to fully degased water, with a sensitivity of 0.13 °C/ppm.

### 3. Analysis of experimental results

Transient pool boiling tests were conducted at atmospheric pressure. Six periods were tested: 5, 10, 20, 50, 70 and 100 ms. The effect of subcooling was also investigated by running tests at saturation condition (0 K), low subcooling (25 K) and very high subcooling (75 K). Each test condition was run several times (three to five times) to check the repeatability of the measurements. All these tests were run with the same heater in order to eliminate the uncertainty associated with the distribution and the size of cavities available on the boiling surface.

#### 3.1. Single phase transient heat transfer
In single phase heat transfer, the system can be modeled as a one-dimensional conduction heat transfer problem due to the large aspect ratio between lateral scales (1 cm x 1 cm) and thickness (1 mm) of the heating area (see Figure 5). The ITO layer is very thin (700 nm) and both its thermal resistance and its thermal capacity are negligible. Therefore, the ITO can be modeled as a planar surface energy source given by \( q_0' e^{t/\tau} \). The thermal resistance between the substrate and air is very high compared to conduction heat transfer in the substrate and thus the air/substrate interface can be assumed adiabatic. The equations governing the system, together with the appropriate initial and boundary conditions are:

\[
\frac{\partial T_s}{\partial t} = a_s \frac{\partial^2 T_s}{\partial z_s^2} \quad (3)
\]

\[
\frac{\partial T_w}{\partial t} = a_w \frac{\partial^2 T_w}{\partial z_w^2} \quad (4)
\]

\[
k_w \frac{\partial T_s}{\partial z_s} \bigg|_{z_s=L_s} - k_s \frac{\partial T_w}{\partial z_w} \bigg|_{z_w=0} = q_0' e^{t/\tau} \quad \forall \ t \geq 0 \quad (5)
\]

\[
T_s \big|_{z_s=L_s} = T_w \big|_{z_w=0} \quad \forall \ t \geq 0 \quad (6)
\]

\[
-k_s \frac{\partial T_s}{\partial z_s} \bigg|_{z_s=0} = 0 \quad \forall \ t \geq 0 \quad (7)
\]

\[
T_w \big|_{z_w=\infty} = T_0 \quad \forall \ t \geq 0 \quad (8)
\]

\[
T_s \big|_{t=0} = T_w \big|_{t=0} = T_0 \quad \forall z_s, z_w \quad (9)
\]

The asymptotic solution of the conduction problem (for \( t \gg \tau \), in general \( 3\tau \) is large enough) can be obtained with the Laplace transform method. The temperature profile evolutions in substrate and water are given by

\[
T_s( z_s, t) = T_0 + q_0' e^{t/\tau} \left[ \cosh \frac{z_s}{L_s \sqrt{F_{0s}}} / \cosh \frac{1}{\sqrt{F_{0s}}} \right] \left[ \frac{E_s}{\sqrt{\tau}} \tanh \frac{1}{\sqrt{F_{0s}}} + \frac{E_w}{\sqrt{\tau}} \right] \quad (10)
\]

\[
T_w( z_w, t) = T_0 + q_0' e^{t/\tau} \left[ \exp \left( -\frac{z_w}{\sqrt{4a_w \tau}} \right) \right] \left[ \frac{E_s}{\sqrt{\tau}} \tanh \frac{1}{\sqrt{F_{0s}}} + \frac{E_w}{\sqrt{\tau}} \right] \quad (11)
\]

where \( F_{0s} = a_s \tau / L_s^2 \) is the asymptotic Fourier number. Thus, the temperature rise on the ITO surface (\( z_w = 0 \) or \( z_s = L_s \)) is

\[
T_h(t) - T_0 = q_0' e^{t/\tau} \left[ \frac{E_s}{\sqrt{\tau}} \tanh \frac{1}{\sqrt{F_{0s}}} + \frac{E_w}{\sqrt{\tau}} \right] \quad (12)
\]

The thermal power released by ITO is transferred partially to sapphire and partially to water

\[
q''_{hs}( t) = k_s \frac{\partial T_s}{\partial z_s} \bigg|_{z_s=L_s} = q_0'' e^{t/\tau} \ E_s \tanh \frac{1}{\sqrt{F_{0s}}} \left[ \frac{E_s}{\sqrt{\tau}} \tanh \frac{1}{\sqrt{F_{0s}}} + \frac{E_w}{\sqrt{\tau}} \right] \quad (13)
\]
\[ q''_{hw}(t) = -k_w \frac{\partial T_w}{\partial z_w} \bigg|_{z_w=0} = q_0'' \frac{e^{t/\tau}}{\tau} \varepsilon_w \left[ \varepsilon_s \tanh \frac{1}{\sqrt{F_o s}} + \varepsilon_w \right] \] (14)

and the ratio of thermal power transferred to water is

\[ R_{hw} = \frac{q''_{hw}(t)}{q''_0 \frac{e^{t/\tau}}{\tau}} = \varepsilon_w \left[ \varepsilon_s \tanh \frac{1}{\sqrt{F_o s}} + \varepsilon_w \right] \] (15)

This term does not depend on time, but only on physical properties and power excursion period. The temperature dependence of the term is shown in Figure 6 for periods from 5 to 100 ms. It can be seen that due to the high thermal diffusivity of sapphire, only a small fraction of the heat released by the ITO coating is transferred to water. The term \( R_{hw} \) depends very slightly on temperature (less than 1% of change from room to saturation temperature). It increases as the power excursion period increase.

However, when the diffusion length scale \( \sqrt{a_s \tau} \) is small compared to the substrate thickness \( L_s \) (and so \( F_o s \) is very small), e.g. for cases at 5 and 10 ms, the substrate acts like an infinite heat sink and the period has little or no effect on \( R_{hw} \), which then approaches \( \varepsilon_w / (\varepsilon_w + \varepsilon_s) \).

Figure 6. Temperature dependence of \( R_{hw} \).

Asymptotic conduction heat transfer coefficients to water and sapphire are given by

\[ h_{w,c} = \frac{q''_{hw}(t)}{T_h(t) - T_0} = \frac{\varepsilon_w}{\sqrt{\tau}} \] (16)

\[ h_{s,c} = \frac{q''_{hs}(t)}{T_h(t) - T_0} = \frac{\varepsilon_s \tanh \frac{1}{\sqrt{F_o s}}}{\sqrt{\tau}} \] (17)

A comparison between measured and analytic temperature rise for highly subcooled tests is shown in Figure 7 as a function of time normalized by the power excursion period (note that experimental data shown in Figure 7 are limited to the single phase heat transfer regime). The theoretical temperature rise curves (labelled “cond”) are obtained from Eq. (12), substituting the theoretical surface power source \( q_0'' \frac{e^{t/\tau}}{\tau} \) with the actual one \( V(t) \cdot I(t) / A_h \):

\[ T_h(t) - T_0 = \frac{V(t) \cdot I(t)}{A_h} \left[ \frac{\varepsilon_s \tanh \frac{1}{\sqrt{F_o s}} + \varepsilon_w}{\sqrt{\tau}} \right] \] (18)
Figure 7. Measured and calculated temperature rise vs. period in tests at 75 K of subcooling (single-phase regime only).

Figure 8 shows a comparison between measured and calculated heat transfer coefficients (note that the error bars are covered by dots). The physical properties for the calculation of the theoretical trends are taken at saturation temperature. The near-perfect agreement between data and theoretical trends confirms the quality of experimental data and the validity of the analytic solution.

Figure 8. Measured and calculated heat transfer coefficient vs. period in the non-boiling regime (all test conditions).

3.2. Onset of nucleate boiling

The ONB conditions are identified by synchronized IR and HSV images. For each test, an ONB time range can be determined depending on when the first bubble appears on HSV and IR recordings. The time in the middle of the range is taken as the nominal ONB time which gives the nominal ONB temperature. The temporal uncertainty (\(e_{te}\)) is calculated by half the difference between the upper limit and lower limit temperature of the ONB time range (100 µs in the worst case). In addition to temporal uncertainty, there is an uncertainty related to the test repeatability. The standard deviation of ONB temperatures from repeated runs is used to represent such uncertainty (\(e_{re}\)). Compared to the temporal and repeatability uncertainties, the nominal instrument uncertainties are much smaller, and therefore can be safely neglected in the present analysis. Since the temporal uncertainty and the repeatability uncertainty are independent and assumed to be Gaussian, the total uncertainty is calculated as below:

\[
e_{tot} = \sqrt{e_{te}^2 + e_{re}^2}
\]  

(19)

Usually, at short periods the total uncertainty is dominated by temporal uncertainty while at long periods by repeatability uncertainty. The ONB heat flux and corresponding uncertainty are calculated using the same procedure as the ONB temperature.

In Figure 9 (left), ONB heat fluxes as functions of the period are shown for tests with 0 K, 25 K and 75 K of subcooling (error bars shown in this figure and in the following figures correspond to ± \(e_{tot}\)). We observe that for the same period the higher is the
subcooling, the higher is the heat flux required to start boiling. In Figure 9 (right), ONB wall superheats show qualitatively the same dependency as ONB heat fluxes.

Figure 9. Heat flux (left) and wall superheat (right) vs. period at the onset of nucleate boiling (all test conditions).

Error bars are present but very small.

A mechanistic ONB model was derived from the combination of Hsu’s criterion [11] and the analytical transient conduction solution. Hsu’s criterion is based on a developing thermal boundary layer model. It states that the bubble can grow out of the nucleation site if the saturation temperature corresponding to the local internal pressure of the vapor embryo is reached or exceeded all over its surface. Since our surface is hydrophilic (i.e. contact angle < 90°), the internal pressure at the tip of the vapor embryo can be expressed by

\[ p_v - p_t = \frac{2\sigma}{r_c} \]  (20)

where we neglected the effect of non-condensable gases and \( r_c \) is the radius of the cavity. By combining Eq. 20 with the transient conduction analytic solution (Eq. 11), the mechanistic ONB model is given by:

\[ q_{w,\text{onb}}'' = \frac{e_w}{\sqrt{T}} [T_{\text{sat}}(p_{\text{atm}} + 2\sigma/r_c) - T_{\text{bulk}}] \exp\left(\frac{r_c}{\sqrt{a_{wT}}}\right) \]  (21)

\[ \Delta T_{\text{sat, onb}} = [T_{\text{sat}}(p_{\text{atm}} + 2\sigma/r_c) - T_{\text{sat}}(p_{\text{atm}})] \exp\left(\frac{r_c}{\sqrt{a_{wT}}}\right) + \Delta T_{\text{sub}} \left[ \exp\left(\frac{r_c}{\sqrt{a_{wT}}}\right) - 1 \right] \]  (22)

Moreover, since the term \( r_c/\sqrt{a_{wT}} \) is close to zero in all our test conditions, Eq. 22 can be conveniently simplified as

\[ q_{w,\text{onb}}'' = \frac{e_w}{\sqrt{T}} [T_{\text{sat}}(p_{\text{atm}} + 2\sigma/r_c) - T_{\text{bulk}}] = h_{w,c} [T_{\text{sat}}(p_{\text{atm}} + 2\sigma/r_c) - T_{\text{bulk}}] \]  (23)

where emerges that the ONB heat flux is proportional to the transient conduction heat transfer coefficient, which in turn is proportional to \( 1/\sqrt{T} \), as shown by Eq. (16).

In our case, the application of the ONB model requires knowledge of the radius (or the distribution of radii) of the micro-cavities (nucleation sites) on the heating surface. Thus, the coordinates of the ONB nucleation site were first identified from the IR image. Then, the heater was examined with the SEM, making it possible to identify the cavity that served as nucleation site at ONB. The size of the imperfection is approximately 5 microns (see Figure 10) which corresponds to \( r_c \approx 2.5 \) µm. Using this value, the ONB heat flux, Eq. (21), and wall superheat, Eq. (22), could be predicted and plotted in Figure 9 (solid colored lines). The ONB model captures the trend of the experimental results quite well, and thus is recommended for prediction of ONB in transient pool boiling.
3.3. Mechanisms of heat transfer from ONB to FDNB

Several boiling heat transfer mechanisms have been identified during the transition from ONB to fully developed nucleate boiling (FDNB). These mechanisms depend on the conditions under which boiling commences, which in turn are determined by the subcooling and power escalation period. To better understand these mechanisms, it is helpful to characterize the conditions of the boiling surface at the ONB moment. It is noteworthy that the growth rate of the heat flux to water and the rate of temperature rise at the measured ONB moment (estimated by differentiating Eq. (14) and Eq. (12) at \( t = t_{onb} \)) depend on the subcooling and the period of the exponential power input, as shown in Figure 11. High subcooling and short periods result in a rapid escalation of heat flux and temperature on the boiling surface. Thus, we can expect that, for high subcooling and short period the activation of new nucleation sites on the boiling surface is much faster than for long periods and low subcooling.

![Figure 10. SEM image of the probable nucleation site](image)

![Figure 11. Calculated rate of rise of the heat flux to water (left) and ITO temperature (right) at the ONB moment](image)

An estimate of the bubble radius at the end of the inertia-controlled phase can be made with the model proposed by Mikic et al. [17] for a uniformly superheated medium. The duration of the inertia-controlled phase \( t^* = 1 \) is given by

\[
t_{ic} = \frac{B^2}{A^2}
\]

and the corresponding bubble radius is

\[
R_{ic} = A t_{ic}
\]
Jas, the thickness of the superheated layer at \(ONB + t_{\text{sat}}\), this rise of the boiling surface temperature is rapid due to the burning of big dry spots below each bubble (0.0328s in video 0K_5ms). Thus, the rewetting of the surface is inhibited and the surface temperature increases rapidly due to the formation of big dry spots below each bubble (0.0328s in video 0K_5ms). Under these circumstances, boiling proceeds from ONB almost instantaneously to CHF.

At subcooled conditions, except for 25 K subcooling and 100 ms, the estimated bubble radii are larger than the superheated layer thickness (see Figure 12). In particular, in highly subcooled conditions, e.g. 75 K, the thickness of the superheated layer at ONB is very small compared to the size of the bubbles at the end of the inertia-controlled phase. Thus, after the inertia-controlled phase, bubbles contract rapidly due to the condensation of the vapor in contact with subcooled liquid (see video 75K_5ms and video 75K_100ms). The rates of heat generation and temperature rise at ONB are much higher than in saturation conditions (see Figure 12).

\[
A = \sqrt{\frac{\pi \Delta T_{\text{sat}} h_{lv} \rho_v}{T_{\text{sat}} \rho_l}} \quad (26)
\]

\[
B = \frac{12}{\pi} J_{a^2} a_l \quad (27)
\]

The bubble radii at the end of the inertia-controlled phase estimated from Eq. (24) are plotted in Figure 12 as a function of period and subcooling (colored dots, labeled BR). An estimate of the superheated layer thickness at ONB is also shown (colored lines, labeled SHL), calculated from Eq. (11) as the thickness for which \(T_w > 100.1 \, ^\circ\text{C}\) when \(t = t_{\text{onb}} + t_{\text{ic}}\).

Figure 12. Comparison between the bubble radii at the end of the inertia-controlled phase and the superheated layer thickness at ONB.

In saturation condition, once a bubble grows out of the cavity, it can successfully grow through the inertia-controlled phase and keep growing by evaporation of the thermal boundary layer surrounding the bubble (thermally-controlled growth) [18]. For long periods, e.g. 100 ms (see video 0K_100ms), a few nucleation sites are activated and generate bubbles of large size, comparable to the length scale of the heating surface (1cm). Bubbles keep growing until they reach the departure diameter. Then, after the detachment, the heating surface is rewetted by water. In this situation, the increase of the heater power is slow compared to the time scale of bubble growth and detachment (see Figure 11). Thus, the heat transfer associated with the nucleation of a few big bubbles vastly exceeds transient conduction and the rise of the boiling surface temperature is abruptly halted. This condition, which we called OBD (Onset of Boiling Driven heat transfer), is reflected by a sharp inflection of the heat transfer curve from the non-boiling transient conduction asymptote (see Sections 3.4 and 3.5). During the boiling process, the evaporation of the liquid microlayer consumes the energy locally released by the heater and also the sensible energy stored in the substrate (see circles with negative heat flux to sapphire, from 0.3876s in video 0K_100ms). As boiling proceeds after OBD, at saturation, this phenomenon can lead to a decrease of the average boiling surface temperature (see Sections 3.4 and 3.5), which is known as overshoot (OV). At short periods, e.g. 5 ms, since the rates of heat generation and temperature rise at ONB are higher than at 100 ms (see Figure 11), more nucleation sites are activated within a short time (see video 0K_5ms). Several big bubbles crowd the heating surface and tend to merge with each other before they can reach the departure diameter, creating a large vapor cushion above the heater. As a result, the rewetting of the surface is inhibited and the surface temperature increases rapidly due to the formation of big dry spots below each bubble (0.0328s in video 0K_5ms). Under these circumstances, boiling proceeds from ONB almost instantaneously to CHF.
Figure 11) and thus a huge number of cavities is rapidly activated. Therefore, shortly after ONB, the boiling surface is completely covered by tiny bubbles that undergo continuous cycles of growth and contraction with frequency comparable to the HSV frame rate, i.e. 5000 Hz. This boiling mechanism is very effective. In fact, in tests with 75 K subcooling and 5 ms of period, heat fluxes as large as 10 MW/m² were reached without undergoing any boiling crisis. It is also noteworthy that, contrary to saturation condition where the thermal behavior is determined by the nucleation and the growth of a few individual bubbles of large size, under highly subcooled conditions, OBD and OV are due to the explosive activation of new nucleation sites on the boiling surface.

At low subcooled conditions, e.g. 25 K, except for 100 ms case, the thickness of the superheated layer at ONB is still smaller than the size of the bubbles at the end of the inertia-controlled phase (see Figure 12). In addition, the rates of heat generation and temperature rise at ONB are still much higher than the ones at saturation condition, although smaller than those at 75 K of subcooling (see Figure 11). At these conditions, bubbles still experience the phases of inertia-controlled growth, condensation and cycles of oscillation as bubbles at 75 K of subcooling (see video 25K_5ms and video 25K_100ms). However, due to the smaller subcooling and thicker superheated layer at ONB, the size of bubbles is larger than the ones at 75 K subcooling and a small number of cavities is activated. As a result, the boiling mechanism is less effective than at 75 K subcooling, although still more effective than saturation condition.

3.4. Transient boiling processes

In transient boiling tests there are generally two types of boiling curves: with temperature overshoot and without temperature overshoot. Several transient boiling steps are identified depending on the type of boiling curves.

![Figure 13. Typical boiling curves with temperature overshoot for the a test at 5 ms and 75K subcooling (left) and without temperature overshoot at 5 ms and 25K subcooling](image)

Figure 13 (left) shows a typical boiling curve with temperature overshoot, where the subcooling is 75 K and the period is 5 ms. Five features are identified with dots of varying color.

Before ONB the boiling curve closely follows single-phase transient conduction. While heat flux to water and wall superheat keep increasing (and so does the superheated layer (SHL) thickness in water), at a certain moment ONB occurs (green dot). Several small standalone bubbles can be seen on the HSV image, but it barely shows any change in the IR image since boiling is still highly localized (0.0376 s in video 75K_5ms and Figure 14[there is no 0.0376s pic in figure 14]).

Shortly after ONB, the boiling curve starts to deviate from the transient conduction asymptote. When more bubbles are generated, the associated heat transfer mechanism supersedes transient conduction. The heat flux increases, whereas the wall superheat does not show a significant increase. The combination of heat flux to water and wall superheat results in an inflection of the boiling curve. Such inflection denotes the occurrence of the onset of boiling driven heat transfer regime OBD (blue dot).

We can clearly see many bubbles and their temperature footprints on the HSV and IR images (0.0380 s in video 75K_5ms and
It is emphasized that at saturation conditions the OBD is achieved by bubble departure and surface rewetting (around 0.4004 s in video 0K_100ms and Figure 15), while at subcooled condition OBD depends on the rapid activation of nucleation sites.

After OBD, boiling becomes more and more vigorous. The heat flux to water increases sharply while the heat flux to substrate decreases significantly. Such conjugate heat transfer among water, substrate and power input causes the wall temperature to drop; this is the overshoot (OV) point (magenta dot in Figure 13, 0.0384 s in video 75K_5ms and Figure 14).

After the OV, the wall superheat keeps decreasing due to the cooling effect of vigorous boiling. However, heat flux to water still increases sharply. This rapid process reaches an end when the SHL is fully depleted (cyan dot in Figure 13). After that, boiling is suppressed. The HSV image shows that bubbles condense and become smaller, while the IR image reveals a lower surface temperature (0.0388 s in video 75K_5ms and Figure 14).

Finally, when the exponential increase of power input catches up with the energy consumption of the system, heat flux to water and to substrate reach a new balance. The boiling curve progresses towards FDNB (red dot in Figure 13, 0.0392 s in video 75K_5ms and Figure 14) which is predicted reasonably well by the Rohsenow correlation [19] with $C_{ef} = 0.0135.$
Figure 14. HSV, ITO temperature and heat flux from OBD to FDNB for the test at 5 ms and 75K subcooling.

Figure 13 (right) shows a typical boiling curve without temperature overshoot, where the subcooling is 25 K and the period is 5 ms. This type of boiling curve usually exists at low period and low subcooling. In such conditions the boiling process presents three steps. Before OBD, the heat transfer regimes are basically the same as for the case with overshoot. However, the boiling process differs after OBD. Instead of progressing through OV and SHL depletion, there is no visible temperature overshoot. Wall superheat increases monotonically at these conditions, which means the power input is always sufficiently high and the SHL is thick enough to support boiling. Eventually, the boiling curve can progress toward FDNB at subcooled condition (0.0356 s in video 25K_5ms and Figure 15) or transfer toward CHF without returning to FDNB at saturation condition (0.0328 s in video 0K_5ms and Figure 16).

Figure 15. HSV, ITO temperature and heat flux to water during the FDNB regime for the test at 5 ms and 25K subcooling.
Figure 16. HSV, ITO temperature and heat flux to water during the fully nucleate boiling regime for the test at 5 ms and 0K subcooling.

The typical boiling curves for three different subcoolings are plotted in Figure 17. For each subcooling, the boiling curve is plotted for three periods i.e. 5ms, 20ms and 100ms, along with the corresponding analytic transient conduction curve (grey lines). The corresponding values predicted by Rohsenow correlation are also plotted (black dashed line). It is clearly shown that, for the same subcooling, the boiling curve is shifted towards higher heat fluxes and higher wall superheats as the period becomes smaller. For the same period, the boiling curve is shifted towards higher heat fluxes and higher wall superheats with increasing subcooling.
3.5. **Onset of boiling driven heat transfer and temperature overshoot**

OBD denotes the beginning of vigorous boiling and its signature is the inflection of the boiling curve from the transient conduction asymptote. In addition, OBD is associated with a sharp decrease of the heat flux transferred to the sapphire substrate due to boiling.

OBD heat fluxes and temperatures are plotted in Figure 18. Although the trends for OBD and ONB are very similar, the values of heat flux and wall superheat for OBD are higher than the ones for ONB. In fact, on a heater with a distribution of cavity sizes, the ONB bubbles are always generated on the largest unflooded cavities which require the lowest heat flux and wall superheat according to Eq. (21) and Eq. (22). However, higher heat flux and wall superheat are required to trigger the nucleation of the remaining smaller cavities which contribute to OBD.
OV wall superheats (if OV is present) are obtained by searching for the first temperature peak on the boiling curve between OBD and the SHL depletion point. The results are plotted in Figure 19. As shown, there is usually no temperature overshoot at short periods and small subcoolings due to rapid increase of heat generation and insufficient enhancement of the boiling heat transfer coefficient. The trend for the OV wall superheat is also similar to the ONB wall superheat. For a given subcooling, the OV wall superheat increases with decreasing power excursion periods. For a given power excursion period, the OV wall superheat increases with increasing subcooling. It is also noteworthy that the OV values at subcooled conditions, i.e. 25 K and 75 K, are close to each other while distant from the ones at saturation conditions. This is likely caused by the different boiling mechanisms at subcooled and saturation conditions, as discussed in Section 3.3.

4. Conclusions

Transient heat transfer phenomena occurring during exponential power escalations were investigated on a plate-type, IR-transparent heater. Exponential periods in the range from 5 ms to 100 ms and bulk temperatures from saturation to 75 K of subcooling have been explored at ambient pressure in pool boiling conditions. Synchronized state-of-the-art diagnostics such as IR thermometry and HSV were used to provide new and unique insight into the transient boiling heat transfer phenomena and to improve the accuracy and the reliability of measured quantities compared to existing studies. Various boiling regimes were observed during the transition from ONB to fully developed nucleate boiling. ONB, OBD and OV conditions were identified, depending on the period of the power escalation and the subcooling.

The main findings are as follows:
The measured single phase heat transfer coefficient, before boiling inception, is inversely proportional to the square root of the period. Moreover, the heat flux to water, the wall temperature rise and the heat transfer coefficient can be predicted by analytic expressions developed from the solution of the 1D transient conduction problem.

The measured ONB heat flux and superheat increase as the period decreases, and can be predicted by a combination of the analytic transient conduction temperature profile in water and the Hsu’s nucleation criterion. Accordingly, ONB was observed on the largest unflooded active cavity available on the heater surface.

The photographic study of the boiling process from ONB to FDNB reveals two different boiling mechanisms. At saturation condition where the thickness of the superheated layer is large, the boiling process depends on the growth and departure of a few individual bubbles with large size. At subcooled conditions where the superheated layer is very thin, the boiling process is promoted effectively by the rapid activation of a large number of nucleation sites. Here the inability of a bubble to grow beyond the thin superheated layer leads to highly localized cooling. In particular, a heat flux as high as 10 MW/m² was reached without undergoing the boiling crisis at 75 K subcooling and 5 ms condition.

The measured OBD heat flux and superheat follow the same trend as ONB; they increase as the period decreases and the subcooling increases. This is to be expected as ONB and OBD are governed by the same physical phenomena. OBD occurs when several nucleation sites are activated, which requires higher superheat and heat flux compared to ONB. We may expect that OBD changes according to the size and the distribution of nucleation sites present on the boiling surface.

Measured OV wall superheat also follows the same trend as ONB superheat; superheat increases as the period decreases and the subcooling increases. However, there is usually no temperature overshoot at short periods and small subcoolings due to a rapid increase of heat generation and insufficient enhancement of the heat transfer coefficient. The measured OV wall superheats are consistent with the observation of different boiling mechanisms at saturation and subcooled conditions.

FDNB conditions are achieved if the rate of heat transfer enhancement is faster than the rate of heat generation, typically at long period, or under subcooled conditions (whether long or short periods are explored). Otherwise, close to saturation conditions, CHF could be reached directly from ONB at short periods.

Follow-up investigations including the study of forced convection effects under the same exponential power escalation scenarios are presented in the companion paper [14].

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Appendix A. Coupled radiation-conduction model

To achieve an accurate estimation of the temperature and heat flux distributions on the boiling surface is necessary to solve a coupled conduction/radiation inverse problem. The problem is inverse because the boundary condition for the conduction problem (the boiling surface temperature) is not known, but is part of the solution. What is known is the radiation measured by the IR camera, which combines the radiation emitted by the boiling surface (ITO in our case), the radiation emitted by the sapphire substrate and also reflection of the background radiation (at ambient temperature), as sketched in Figure 20. With this technique we can estimate the time-dependent 3D temperature distribution in the heater, as well as local temperature and local heat flux distributions on the boiling surface, starting from the time-dependent 2D radiation measured by the IR camera. A brief description of this technique is given below. Further details can be found in Ref. [16].

![Figure 20. Sketch of the optical setup.](image)

A.1. Conduction model

The transient heat transfer equation in the substrate physical domain is discretized with an implicit 3D finite volume scheme. The boundary corresponding to the active ITO coating serves as temperature boundary condition. Its local temperature $T_{ito}(x,y)$ is determined according to the radiation recorded by the infrared camera, as described later. All other boundaries are modelled as diabatic surfaces: appropriate heat transfer coefficient $h$ and sink temperature $T_\infty$ have to be assigned for each surface. Once a converged solution is achieved for a prescribed ITO temperature, the heat flux to sapphire at the ITO-sapphire interface can be simply calculated by the discretized Fourier’s conduction law

$$ q_s'(t) = k_s(T_{ito}) \frac{T_{ito}(x,y,t) - T_s(x,y,zc,t)}{z_c} \quad (28) $$
where $z_c$ is the distance between the ITO boundary and the center of the adjacent cell, and $k_s(T_{ito})$ is the sapphire thermal conductivity at the ITO temperature. An estimate of the local instantaneous heat flux to water $q'_w$ can thus be obtained subtracting the total power $q_{tot}'$ generated by Joule heating in the ITO and the heat flux transferred to sapphire

$$ q'_w(x, y, t) = q'_{tot}(t) - q'_s(x, y, t) = \frac{V(t) \cdot I(t)}{A_h} - k_s(T_{ito}) \frac{T_{ito}(x, y, t) - T_s(x, y, z_c, t)}{z_c} \quad (29) $$

A.2. Radiation model

The radiation measured by the IR camera includes the radiation emitted by the ITO coating, the radiation emitted by the sapphire substrate and the reflection of the background radiation, as sketched in Figure 20.

The radiation model is inspired by the radiation model proposed in the work of Kim et al. [20]. However, the present model is not based on average energy radiance, but spectral photon radiation. This is necessary because sapphire has a highly variable spectral absorption coefficient in the range of wavelengths between 4 and 5 µm. Photons are emitted by the ITO and by the substrate. Water emissions are completely shielded by the ITO layer, which is opaque in the range 3 to 5 µm used in our investigations. We have assumed that the light source is planar, that is, light is only emitted in the direction normal to the boiling surface (2D radiation normal to the x-y plane).

Emissions from the ITO

The spectral photon flux per wavelength emitted by a black body surface is

$$ N_{p\lambda} = N_{p\lambda}(T, \lambda) = \frac{E_{p\lambda}(T, \lambda)}{e_{\lambda}} = \frac{2 \pi c}{\lambda^4} \left( \frac{c}{e^{cT/\lambda} - 1} \right) \quad (30) $$

Since ITO is thick enough to be opaque and thin enough to neglect temperature gradient across its thickness, the spectral photon flux emitted at the ITO/substrate interface is

$$ N_{p\lambda, T_{ito}} \cdot (1 - \rho_{\lambda, hs}) \quad (31) $$

where $\rho_{\lambda, hs}$ is the spectral reflection coefficient at the interface between ITO and sapphire. To obtain the effective photon flux emitted by the ITO, one must take into account multiple reflections at the ITO/substrate and substrate/air interfaces and absorption within the substrate, as sketched in Figure 21. Summing all the contributions we get

$$ N_{p\lambda}^{ito} = N_{p\lambda, T_{ito}} \left(1 - \rho_{\lambda, hs}\right) \tau_{\lambda, s} (1 - \rho_{\lambda, sa}) \sum_{n=0}^{\infty} (\rho_{\lambda, hs} \rho_{\lambda, sa} \tau_{\lambda, s}^2)^n = N_{p\lambda, T_{ito}} \frac{(1 - \rho_{\lambda, hs}) \tau_{\lambda, s} (1 - \rho_{\lambda, sa})}{1 - \rho_{\lambda, hs} \rho_{\lambda, sa} \tau_{\lambda, s}^2} \quad (32)$$

$$ = N_{p\lambda, T_{ito}} \tau_{\lambda, app} $$
**Emissions from the sapphire substrate**

A substrate layer of thickness $dz$ emits a photon flux equal to $\alpha_3 N_{\lambda,T(z)} dz$ in two directions. Half of the flux is emitted forward, towards the camera, half is emitted backward, towards the ITO heater. In the first case, the spectral photon flux reaching the substrate/air interface is

$$N_{p\lambda}^{s,+} = \frac{1}{2} \int_0^L \alpha_3 N_{p\lambda,T(z)} \exp(-\alpha_3(L - z)) \, dz \quad (33)$$

In the second case, the photon flux reaching the ITO/substrate interface is given by

$$N_{p\lambda}^{s,-} = \frac{1}{2} \int_0^L \alpha_3 N_{p\lambda,T(z)} \exp(-\alpha_3z) \, dz \quad (34)$$

Part of this flux is reflected back at the substrate/ITO interface and crosses the substrate to reach the substrate/air interface. At the substrate/air interface, the two light beams can be transmitted or reflected. Once multiple reflections and absorptions are accounted for (see Figure 22 and Figure 23), the effective spectral photon flux crossing the substrate/air interface is

$$N_{p\lambda}^s = \frac{N_{p\lambda}^{s,-} \rho_{\lambda,hs} \tau_{\lambda,s} (1 - \rho_{\lambda,ss}) + N_{p\lambda}^{s,+} (1 - \rho_{\lambda,sa})}{1 - \rho_{\lambda,hs} \rho_{\lambda,sa} \tau_{\lambda,s}^2 \rho_{\lambda,ss}} = N_{p\lambda}^{s,-} \epsilon_{\lambda,app} + N_{p\lambda}^{s,+} \epsilon_{\lambda,app} \quad (35)$$
**Figure 22.** Multiple absorption and reflections determining the apparent backward emissivity $\epsilon_{\text{app}}$ of sapphire.

<table>
<thead>
<tr>
<th>WATER</th>
<th>ITO</th>
<th>SAPPHIRE</th>
<th>AIR</th>
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<tr>
<td>$N_{\text{p,s}}^{\text{k}} \to$</td>
<td>$N_{\text{p,s}}^{\text{k}} \cdot \rho_{\text{hs}}$</td>
<td>$N_{\text{p,s}}^{\text{k}} \cdot \rho_{\text{hs}} \cdot t_{\lambda,s}$</td>
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**Figure 23.** Multiple absorption and reflections determining the forward apparent emissivity $\epsilon_{\text{app}}$ of sapphire.
Part of the signal reaching the IR camera is due to reflection of the background emission at the ITO/substrate and substrate/air interfaces. The atmosphere emits like a blackbody, and the spectral photon flux reflected by the heater (see Figure 24) is given by

\[ N_{p\lambda} = N_{p\lambda,T_a} \left( \rho_{\lambda,sa} + \frac{\rho_{\lambda,hs} \tau_{\lambda,sa}^2 \left( 1 - \rho_{\lambda,sa} \right)}{1 - \rho_{\lambda,hs} \rho_{\lambda,sa} \tau_{\lambda,sa}^2} \right) = N_{p\lambda,T_a} \rho_{\lambda,app} \]  

(36)

**Figure 24.** Multiple absorption and reflections determining the heater apparent reflectivity \( \rho_{\lambda,app} \).

### Overall radiation

The spectral overall photons flux emitted at the substrate/air interface is given by

\[ N_{p\lambda} = N_{p\lambda,T_h} \tau_{\lambda,app} + N_{p\lambda,T_a} \rho_{\lambda,app} + N_{p\lambda,T(z)}^< \epsilon_{\lambda,app}^< + N_{p\lambda,T(z)}^> \epsilon_{\lambda,app}^> \]  

(37)

Then, spectral fluxes can be integrated over the range of interest (3 to 5 \( \mu \)m) to obtain the effective photons flux

\[ N_p = \int_{\lambda_1}^{\lambda_2} N_{p\lambda} d\lambda = \int_{\lambda_1}^{\lambda_2} N_{p\lambda,T_h} \tau_{\lambda,app} d\lambda + \int_{\lambda_1}^{\lambda_2} N_{p\lambda,T_a} \rho_{\lambda,app} d\lambda + \int_{\lambda_1}^{\lambda_2} N_{p\lambda,T(z)}^< \epsilon_{\lambda,app}^< d\lambda + \int_{\lambda_1}^{\lambda_2} N_{p\lambda,T(z)}^> \epsilon_{\lambda,app}^> d\lambda \]  

(38)

Only a fraction of the photons emitted by the heater is directed towards the lens and can reach the IR camera sensor. The final flux depends essentially on the lens focal number \( n_f \) and can be estimated by

\[ \frac{N_p}{4 n_f^2} \tau_{os} \]  

(39)

where the transmission efficiency of the optical setup \( \tau_{os} \) (mirror and lens) is also accounted for.

### Camera model

An IRC806 high-speed infrared camera with an InSb photon detector is used. Each pixel of the InSb sensor has a well \( W_e \) of 7 million electrons. Every time a photon hits the pixel, one electron is moved from the valence to the conduction band.
phenomenon creates a voltage difference proportional to the photon flux, which is the signal measured as photon counts, $R$. The quantum efficiency of the sensor, $\text{QE}$, which is determined by the photon/electron conversion efficiency (internal quantum efficiency), as well as reflection on the surface of the sensor (external quantum efficiency), must be also taken into account.

To convert camera counts to photons, the contribution of the noise must be cancelled. This is given by empty well counts $n_{\text{cw}}$ when the integration time $t_{\text{int}}$ is zero (approximately 420 counts, to be measured before each experimental campaign) and the dark current ($n_{\text{dc}} = 9570$ counts/second as per manufacturer specifications), whose noise is proportional to the integration time $t_{\text{int}}$ ($200 \ \mu\text{s}$). The effective photons flux measured by the camera is thus given by

$$ N_{\text{IRC}}^{\text{p}} = \frac{R - (n_{\text{cw}} + n_{\text{dc}} \cdot t_{\text{int}})}{t_{\text{int}}} \cdot \frac{W_e}{(n_{\text{fw}} - n_{\text{cw}})} \cdot \frac{1}{\text{QE} \cdot A_{\text{pixel}}} $$

(40)

where $n_{\text{fw}}$ is the full well counts when the signal is saturated (approximately 16000 counts, to be measured before each experimental campaign) and $A_{\text{pixel}}$ is the area of the sensor pixel ($20 \ \mu\text{m} \times 20 \ \mu\text{m}$).

A.3. Coupled conduction/radiation model

The flow chart of the coupled conduction/radiation model is shown in Figure 25. At a given time step, the local distribution of photon counts $R$ from the IR camera is obtained. Then a guess of the local heater temperature $T_{\text{ito}}$ is made based on the photon counts $R$. The temperature distribution through the substrate $T^*$ is calculated by the heat conduction code as detailed in Sec. 2. Then, the overall emission of the heater $N_p$ is calculated as detailed above and converted to photon counts as follows

$$ R^* = N_p \cdot t_{\text{int}} \cdot \frac{W_e}{(n_{\text{fw}} - n_{\text{cw}})} \cdot \frac{1}{\text{QE} \cdot A_{\text{pixel}}} + (n_{\text{cw}} + n_{\text{dc}} \cdot t_{\text{int}}) $$

(41)

If the difference of photon counts $|R^* - R|$ is less than a prescribed tolerable error, as explained below, the guessed temperature of ITO heater is accepted and the algorithm is moved to the next time step, otherwise, the code keeps iterating with an adjusted guess of the ITO temperature as boundary condition.

![Flow chart of the coupled conduction-radiation model](image)

**Figure 25.** Flow chart of the coupled conduction-radiation model.

It should be noted that verification of the conduction/radiation coupling is required before every experimental campaign (every heater and optical setup). Fine tuning of the product $\tau_{\text{to}} \cdot \text{QE}$ is also necessary to reduce the error on the measured photons flux.
This is normally achieved by in-situ steady-state calibration (with uniform temperature within the heater), to be run before every experimental campaign (see Figure 26). Optimal values of the τos QE product are usually between 0.7 and 0.9, where we assume that the quantum efficiency does not depend on the wavelength. It is emphasized that this is the only empiricism required in the whole model.

Figure 26. Comparison between measured and calculated radiation in steady-state conditions (uniform temperature).

The radiation model curve in Figure 26 can be approximated with a polynomial $P_{\text{cal}}(T)$ that can be used as “steady-state” calibration curve. Even though this polynomial is not appropriate for accurate time-dependent local temperature measurements, it provides meaningful information on how the radiation changes as a function of temperature. We use this information to adjust the iterative ITO temperature in the conduction/radiation loop (see Figure 25). The iterative temperature distribution at the iteration $n+1$ is calculated as

$$T_{\text{ITO}}^{n+1}(x,y,t) = T_{\text{ITO}}^{n}(x,y,t) - \frac{R'(x,y) - R(x,y)}{\frac{dP_{\text{cal}}}{dT}|_{T_{\text{ITO}}^{n}(x,y,t)}}$$

We consider that the model has converged in a time step when the maximum local temperature adjustment is smaller than $10^{-4}$ °C.

$$\max \left( \frac{|R'(x,y) - R(x,y)|}{\frac{dP_{\text{cal}}}{dT}|_{T_{\text{ITO}}^{n}(x,y,t)}} \right) < 10^{-5}$$

Using this method, the convergence of the conduction/radiation model is normally achieved in less than 5 internal iterations.

A.4. Optical properties

Fundamental and apparent optical properties required for the implementation of the radiation model were measured as detailed in Ref. [16] by means of a FTIR Bruker spectrometer. Fundamental optical properties are shown in Figure 27. Apparent optical properties are shown in Figure 28.
Figure 27. Fundamental optical properties of the ITO-sapphire heater.

Figure 28. Apparent optical properties of the ITO-sapphire heater.
References

### Nomenclature

#### Latin letters

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#### Greek letters

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### Acronyms

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<td>Indium-Tin oxide</td>
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