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Exponential vaporization fronts and critical heat flux in pool boiling

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Abstract

Here we study the inception and propagation of vaporization fronts and transition to the critical heat flux (CHF) and film-boiling regime triggered by a steep, almost instantaneous increase in the heat release from a strip heater submerged in Novec 7300 liquid. The propagation path of the resulting vaporization front along the strip heater is measured and shown to be exponentially increasing in time, in distinction from the previous reports in literature claiming that the increase is only linear. Since the previous experiments employed such liquids as water, refrigerants, acetone, ethanol, and alkali metals, which possess relatively high latent heat of evaporation and thus require a relatively high power to be supplied, the heater burnout at the inception of the CHF and film boiling was too fast to allow for longer-time observations. Accordingly, the previous works observed only an extremely short-time asymptotics of the propagation process, which means the short-time expansion of the exponential function, which is linear. On the other hand, in the experiments with Novec 7300 liquid, the heater burnout is delayed due to a much lower latent heat of evaporation, thus allowing for a much longer observation of the propagation path, which appears to be exponentially increasing in time. The experiments were preceded by our theoretical prediction of such a behavior, and this theory is also described in the present work. Due to the fact that this theory has been corroborated by the experimental data, the theory yields an adequate explanation and description of the CHF trigger and film boiling inception.

Keywords

Heat transfer; Boiling crisis; Critical heat flux; Incipient boiling; Vaporization front

1. Introduction

Pool boiling, and especially the inception of the detrimental critical heat flux (CHF) regime, is a complicated physical phenomenon which is not fully understood, even though multiple experiments were conducted and revealed abundant empirical information [1,2]. Pool boiling is highly effective in heat removal since it involves significant latent heat of evaporation associated with the nucleate boiling regimes, which guarantees high heat fluxes. This is an attractive feature for cooling of high-power microelectronics in ground and space applications [3–7], metallurgical quenching [1], etc. The severe limitation on the heat

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removal in pool boiling, namely the inception of the boiling crisis or the CHF sets in in the most attractive domain of the heat flux regimes, which, unfortunately, results in a rapid, practically uncontrollable bubble merging at the heater surface and transition to film boiling. The resulting vapor film hovering over the heater surface drastically diminishes the heat removal rate, which leads to a rapid burnout of the heater and, in particular, to failure of microelectronics components. Different methods were employed to enhance heat removal in pool boiling, e.g. deposition of nanofibers on the heater surface [4–7], nano-porous textured finishes [8], embedded arrays of low-conductive epoxy [9], modification of the surface wettability [10,11], and miniaturization [12]. Such measures were able to delay the CHF onset, but definitely not to fully eliminate it. Further works have also aimed at a better understanding of the boiling crisis and ascertained some aspects of the bubble merging as a critical percolation phenomenon [13], as well as attributed the heater dry-out at the onset of boiling crisis to the effect of the vapor recoil force at the bubble footprint [14]. Direct numerical simulation methods which aim at modeling of pool boiling, not to mention the CHF itself, are still insufficiently mature [5,15].

When a step-wise increase in power is experienced by a heating element, a direct transition to film boiling may occur, bypassing entirely the nucleate boiling regime, which is sometimes referred to as the third heat-transfer crisis [16–20]. Then, the nucleating bubbles on the heater surface rapidly spread, resulting in formation and propagation of vaporization fronts that merge and fully encase it. A number of works reported that vaporization fronts propagate with a constant velocity [18,19,21–24]. These works employed water (the latent heat of evaporation $L = 2260$ kJ/kg) [21,25], refrigerants ($L = 246.7$ kJ/kg for refrigerant FC-C318 Freon) [22,26], acetone ($L = 515$ kJ/kg) [16,27], ethanol ($L = 844$ kJ/kg) [20,27], alkali metals (for potassium $L = 2023$ kJ/kg, and for cesium $L = 497$ kJ/kg) [20,28], n-pentane ($L = 356$ kJ/kg), [23,29], etc. [17,24,30]. The assumption of a constant velocity of vaporization fronts was embedded as a cornerstone in a number of theories of the inception of this phenomenon [18,19,21,22]. It should be emphasized that all the liquids employed in such experiments so far, possess relatively high latent heats of evaporation, and accordingly, the heaters were subjected to a relatively high power supply to trigger vaporization fronts. As a result, the heaters were burnt very rapidly after the inception of the vaporization fronts, and in this short-time limit any dependence of the propagation path on time would be inevitably linearized resulting in pseudo-constant propagation velocities. Therefore, the real nature and character of the vaporization front incipience and propagation could be explored only in the experiments with liquids with the lowest latent heat of evaporation (e.g. Novec 7300 liquid with $L = 101.67$ kJ/kg), which allow for longer observation times. This is undertaken in the present work, with the corresponding theory of the transition to the CHF and film boiling proposed as well.

2. Experimental

2.1. Materials

For the experiments conducted here, 3M Novec 7300 liquid was used as a working fluid. The thermal diffusivity of Novec 7300 is $\alpha_L = 3.57 \times 10^{-8}$ m²/s, the density $\rho_L = (1.7162 - 0.0024 T) \times 10^3$ kg/m³ (with T being temperature in °C) [31]. The Kanthal A-1 flat resistive

strips of $0.4 \text{ mm} \times 0.1 \text{ mm}$ (width $\times$ thickness) and $0.5 \text{ mm} \times 0.1 \text{ mm}$ (width $\times$ thickness), both 30 mm in length, were used as the heating elements.

2.2. Experimental setup

Experiments were conducted using the setup shown in Fig. 1. The pool filled with Novec 7300 liquid was made of two aluminum and two borosilicate glass walls. The two opposing borosilicate glass walls allowed for the observations using a high-speed camera. The other two walls and the bottom were made of aluminum. A polycarbonate plate with a through hole (to sustain the free surface of the liquid at the atmospheric pressure) was located on top to act as a condenser and to minimize the loss of Novec 7300 liquid. An additional stainless steel resistive wire heater was inserted in the pool (cf. Fig. 1a) to heat up the working fluid close to the boiling temperature (the saturation temperature at the atmospheric pressure of Novec 7300 is 98°C). The temperature of the liquid in the pool was monitored by a thermocouple (Omega 5TC-TT-T-30-30).

A specially designed fixture, Fig. 1c, was used to clamp the flat Kanthal resistive strip. After each experiment with the vaporization front inception, the resistive strip was replaced. The strip was horizontal and stretched between two copper plates mounted at the opposing sides of a polycarbonate fixture to ensure the electrical contact (cf. Fig. 1c). A threaded rod disjoined the lower part of the poly-carbonate fixture to stretch the strip (the heating element) and to ensure that it would be straight and horizontal. The copper plates were connected to a DC power supply which was triggered to provide a practically instantaneous step-wise increase in the Joule heat flux in the Kanthal resistive strip.

The applied voltage at the strip was monitored using an oscilloscope (Tektronix model TDS 210) connected to the copper plates. A multi-meter (Fluke model 8845A) was also used to measure the strip resistance prior to the experiments. It should be emphasized that the Kanthal strip used as the heating element possessed the coefficient of temperature $CT = 1.0$ in the temperature range of up to 480°C . That means that the strip resistance practically did not change in spite of the Joule heating. Thus, the resistance measured at room temperature was used in the calculations of the heat flux q , as $q = V^2/AR$, where V is the voltage measured by the oscilloscope, A is the total surface area of the strip, and R is the resistance of the Kanthal strip measured by the multimeter at room temperature.

2.3. Observation

The inception and propagation of vaporization fronts on the strip heater resulting from a nucleated bubble was recorded by a high-speed camera (Phantom V210) at 10,000 fps using an LED light source for illumination. Snapshots were extracted from the video and analyzed using ImageJ to calculate the initial radius of the nucleated bubble and track the location of the vaporization front in time. Then, the velocity of the vaporization front was also calculated.

3. Theoretical model of the vaporization front

An instantaneous inception of a vapor pocket on a uniformly heated surface, subjected to a constant heat flux q_∞ , is depicted in Fig. 2. The emerged vapor pocket is seen as a cut at the

central section of the horizontal axis, which interrupts the heat transfer at that place. The vapor pocket essentially ‘cuts’ the heat flux through this section, since vapor is a very poor heat conductor compared to liquid. Accordingly, the heat removal from the heater surface through the pocket ceases and the temperature field and thus, the heat flux, should readjust over the rest of the heater surface and in the surrounding liquid. Such a transient readjustment process is predominantly conductive. For a characteristic vapor pocket size c , the characteristic readjustment time in Novec 7300 liquid is of the order of $\tau_L \sim c^2/\alpha_L$, and in the metal heater in contact with it, it is of the order of $\tau_m \sim c^2/\alpha_m$. Since the thermal diffusivity of Novec 7300 at 100 °C $\alpha_L \approx 10^{-4} \text{ cm}^2/\text{s}$ [31] is much smaller than that of Kanthal $\alpha_m \approx 10^{-2} \text{ cm}^2/\text{s}$, $\tau_L \gg \tau_m$, and thus the thermal readjustment in the metal heater is essentially instantaneous in comparison to the thermal readjustment in Novec 7300 liquid. That means that an intermediate asymptotic stage arises in which the temperature field in the metal heater is already stationary, and the heat flux surpasses the vapor pocket, whereas in the liquid the temperature field is essentially the same as before the vapor pocket has been formed.

Accordingly, consider the readjusted quasi-steady temperature field in the metal heater using for simplicity a planar model. Thus, the readjusted temperature field in the metal heater, with the heat flux surpassing the vapor pocket, as shown in Fig. 3 at $y < 0$, satisfies the Laplace equation

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = 0 \quad (1)$$

with the Cartesian coordinate system x and y centered at the pocket center (cf. Fig. 2).

Introduce a function $\phi(x,y)$ related to the temperature field $T(x,y)$ by the Cauchy-Riemann conditions [32–34].

$$\frac{\partial \phi}{\partial x} = \frac{\partial T}{\partial y}, \quad \frac{\partial \phi}{\partial y} = -\frac{\partial T}{\partial x} \quad (2)$$

which allows one to introduce the complex potential $\chi_T(z) = -k_m[\phi(x,y) + iT(x,y)]$ where $z = x + iy$, i is the imaginary unit, and k_m - the thermal conductivity of metal heater.

Then, the first derivative

$$\frac{d\chi_T}{dz} = q_y + iq_x \quad (3)$$

determines the heat flux components in metal according to the Fourier law.

The function $d\chi_T/dz$ is an analytic function of z . Given the analytic continuation [32–34] of the lower half-plane to the upper half-plane, as shown in Fig. 3, and the fact that $q_y = 0$ at $|x| < c$, $q_x = 0$ at $|x| > c$ and $q_y = q_\infty$ at $|y| \rightarrow \infty$, this function is found as

$$q_y + iq_x = \frac{q_\infty z}{\sqrt{z^2 - c^2}} \quad (4)$$

Note that formally this problem is related to the problem of an impact of a plate onto a free liquid surface, with some additional details available elsewhere [35].

Eq. (4) yields the components of the heat flux at the heater surface $y = 0$, as

$$\begin{aligned} q_y = 0, \quad q_x = -\frac{q_\infty x}{\sqrt{c^2 - x^2}} \quad \text{at } |x| < c; \\ q_y = -\frac{q_\infty x}{\sqrt{x^2 - c^2}}, \quad q_x = 0 \quad \text{at } |x| > c \end{aligned} \quad (5)$$

These heat flux distributions in the metal heater arise due to the vapor pocket. Without the vapor pocket, it would be $q_y \equiv q_\infty$, $q_x \equiv 0$ at $y = 0$.

The liquid surrounding a vapor pocket receives more heat than it has received before this pocket had been nucleated. This extra heat will lead to an enhanced evaporation at the vapor pocket margins. That is the physical reason that the pocket boundary will begin to propagate and a vaporization front will be formed. The extra heat Q received by liquid during time t is found as

$$\Delta Q = \left[\int_c^x q_y|_{y=0} dx - q_\infty(x - c) \right] \Delta t = \left[q_\infty \sqrt{x^2 - c^2} - q_\infty(x - c) \right] \Delta t \quad (6)$$

In particular, in the immediate vicinity of the vapor pocket, $x = c + \delta$, in the leading order one obtains from Eq. (6)

$$\Delta Q = q_\infty \sqrt{2c} \Delta \delta \Delta t \quad (7)$$

This heat is spent as the latent heat of evaporation which sustains propagation of the vapor pocket edge, i.e. the vaporization front. Denote the specific latent heat of evaporation as L , and estimate the thickness of the overheated liquid layer in contact with the heater in the vicinity of the vapor pocket edge as $\sqrt{\alpha_L \Delta t}$. Then,

$$\Delta Q = \rho_L L \Delta \delta \sqrt{\alpha_L \Delta t} \quad (8)$$

where ρ_L is the liquid density.

Combining Eqs. (7) and (8), one arrives in the limit $t \rightarrow 0$ at the following expression for the velocity of the vaporization front

$$\frac{dc}{dt} = \left(\frac{q_\infty}{\rho_L L} \right)^2 \frac{2c}{\alpha_L} \quad (9)$$

Integrating Eq. (9) from the initial vapor pocket size $c = c_0$ at $t = 0$, the following exponential law is found for the location of the propagating vaporization front

$$c = c_0 \exp \left[\left(\frac{q_\infty}{\rho_L L} \right)^2 \frac{2}{\alpha_L} t \right] = c_0 \exp \left(\frac{t}{\tau_c} \right) \quad (10)$$

where the characteristic time $\tau_c = \alpha_L (\rho_L L / q_\infty)^2 / 2$.

Accordingly, the velocity of the propagating vaporization front $V = dc/dt = (c_0 / \tau_c) \exp (t / \tau_c)$.

4. Results and discussion

Vaporization fronts were observed propagating over the flat Kanthal resistive strip submerged into Novec 7300 liquid. After a step-wise increase in the applied power on the strip, which resulted in the heat flux above the CHF, the incipience of a nucleated bubble occurred. It triggered the formation and propagation of a vaporization front, which could ultimately encase the entire heater, or to merge with the other fronts propagating from the other bubbles (if any) with the same outcome. Such bubble nucleation occurred either at the edge of the Kanthal strip near the clamp or near the center of the strip at an etched location. Note that the CHF in Novec 7300 liquid sets in at approximately $q_\infty = 20 \text{ W/cm}^2$ [6], and the stepwise heat fluxes applied in the experiments were above this limit. Fig. 4 shows the sequence of images of vaporization fronts propagating from a nucleated bubble for the applied heat flux of $q_\infty = 46.25 \text{ W/cm}^2$ in Novec 7300 liquid at the temperature of 95°C , close to the saturated temperature at the atmospheric pressure, of 98.0°C [31].

Several heat fluxes ranging from $q_\infty = 46.25 \text{ W/cm}^2$ to 53.37 W/cm^2 were applied to the Kanthal resistive strip to trigger and observe the exponential vaporization fronts. The dependences of the measured location and velocity of the vaporization fronts are compared to the theoretical dependences of Eqs. (9) and (10) in Fig. 5.

Fig. 5 clearly shows that the time dependence of the location of the vaporization fronts is non-linear, and their velocity is not constant, in distinction from the previous works [18,19,21–24]. This stems from the fact that the observation times in all previous works were too short compared to the characteristic time τ_c [cf. (Eq. 10)]. For example, for the experiments [21] conducted with water, $\alpha_L = 1.43 \times 10^{-7} \text{ m}^2/\text{s}$, $\rho_L = 1000 \text{ kg/m}^3$, $L = 2260 \text{ kJ/kg}$, and $q_\infty \sim 12.5 \times 10^6 \text{ W/m}^2$, the characteristic time $\tau_c \approx 2.3 \text{ ms}$, whereas the

observations were typically conducted only up to 2.5 ms, not long enough to recognize the nonlinearity. In the case of n-pentane [23], $\alpha_L = 8.1 \times 10^{-8} \text{ m}^2/\text{s}$, $\rho_L = 626 \text{ kg/m}^3$, $L = 357 \text{ kJ/kg}$, and $q_{\infty} \sim 1.6 \times 10^5 \text{ W/m}^2$, the characteristic time $\tau_c \approx 80 \text{ ms}$, whereas the observations were conducted for not $> 100 \text{ ms}$, close to the characteristic time. On the other hand, in the present case of Novec 7300 liquid the characteristic time $\tau_c \approx 2 \text{ ms}$, whereas the observation times are up to 6.8 ms, which fully reveals the nonlinearity, as shown in Fig. 5. In particular, the exponential, rather than linear, propagation of the vaporization fronts in time predicted theoretically [(Eq. 10)] is fully confirmed by the experiment.

An additional trial was conducted using the $0.5 \text{ mm} \times 0.1 \text{ mm}$ Kanthal resistive strip at the heat flux of $q_{\infty} = 31.6 \text{ W/cm}^2$. The location and velocity of the vaporization front compared to the theoretical predictions of Eqs. (9) and (10) are shown in Fig. 6. The agreement of the theory with the data is fairly good and ascertains the fact that vaporization fronts are exponential.

Because the bubble nuclei are smaller than the strip width ($w = 0.4$ or 0.5 mm), the strip geometry at the onset of vaporization fronts is representative of any planar 2D heater. In addition, in the planar case the curvature of a circular vaporization front rapidly becomes negligibly small as its radius increases. Accordingly, the arc length of a section of a circular vaporization front leaning at an angle γ , $c\gamma$ (with c considered as the radius of the circular front), is practically equal to the supporting chord length $2c \sin \gamma/2$ when $w/c \sim 0.1$ (as in the results in Figs. 5 and 6), since $2 \sin 0.05 \approx 0.1$. Thus, also in this limit the vaporization fronts propagating over the flat Kanthal resistive strips are a good approximation of circular vaporization fronts propagating over a planar heater.

Note also, that in the case of natural convection, the characteristic velocity of the Rayleigh-Benard flow, V_{RB} , can be estimated as $V_{RB} = (g\beta Th)^{1/2}$, with g being gravity acceleration, β being the thermal expansion coefficient, T being the surface superheat, and $h \sim 1 \text{ cm}$ being the characteristic depth of the liquid layer. For Novec 7300 liquid, the parameter estimates under the boiling conditions are $\beta = 0.0013 \text{ K}^{-1}$ and $T = 25 \text{ K}$. Then, $V_{RB} = 0.056 \text{ m/s}$. Accordingly, the characteristic time of heat transfer in natural convection is on the scale of 0.1 s , which is one to two orders of magnitude longer than the characteristic time of the vaporization front propagation in the present experiments, and the convective effects can be safely neglected.

The present theory essentially treats the vaporization front as a moving contact line and predicts an infinite (but integrable!) heat flux at its tip. This prediction is in full agreement with a strong enhancement of the local heat flux in the contact line region observed in pool boiling in [36,37].

It should be emphasized that the present theory does predict a threshold heat flux required for a vaporization front to start propagating, and thus, the CHF inception to occur. Specifically, if the heat flux q_{∞} would become small such that the characteristic time of vaporization front propagation τ_c would reduce to the order of the characteristic thermal readjustment time in liquid τ_L , the heat supplied by the heater would be removed from the vapor pocket faster than evaporation at its margin can happen, and the front propagation

would not occur. Then, the critical heat flux for the inception of the vaporization front, and thus the CHF trigger, reads

$$q_{\infty, CHF} \sim \frac{\alpha_L \rho_L L}{c_0} \quad (11)$$

Taking for the estimate the parameters of Novec 7300 liquid $\alpha_L = 3.57 \times 10^{-8} \text{ m}^2/\text{s}$, $\rho_L = 1.71 \times 10^3 \text{ kg/m}^3$, $L = 101.67 \text{ kJ/kg}$, as well as $c_0 \sim 10^{-4} \text{ m}$, one obtains from Eq. (11) $q_{\infty, CHF} \sim 6.2 \text{ W/cm}^2$. This estimate is in reasonable agreement with the value of $q_{\infty, CHF} = 20 \text{ W/cm}^2$ reported in [6]. Therefore, vaporization front propagates only at $q_{\infty} > q_{\infty, CHF}$.

5. Conclusion

The experiments conducted with Novec 7300 liquid allow long-time observations of propagation of the vaporization fronts triggered by a step-wise increase in the power supply to a flat strip heater creating conditions beyond the critical heat flux (CHF). The experiments revealed the exponential law of propagation of the vaporization fronts, which is also fully confirmed by the theory developed in this work. The leading edge of the vaporization fronts covers the distance c in time t given as $c = c_0 \exp(t/\tau_c)$, with τ_c being the characteristic time determined by the physical parameters of the liquid and the supplied heat flux. This exponential law can be observed when the observations are sufficiently longer than τ_c , as in the present experiments with Novec 7300 liquid. On the other hand, in all previous works the other liquids were used and only the conditions $t \ll \tau_c$ were realized. Accordingly, only the linearized asymptotics of the propagation law were realized, with the misleading conclusion that the velocity of the vaporization fronts is constant. In reality, however, it increases exponentially in time.

The present theory does predict that the vaporization front propagation can occur only after a critical heat flux has been achieved, i.e. it predicts the threshold heat flux for the CHF phenomenon to occur in agreement with the experiments.

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Fig. 1. The experimental setup. (a) Schematic, and (b) the image. (c) Detailed sketch of the specially designed fixture with clamped flat Kanthal resistive strip.

Fig. 2.

Inception of a nucleated vapor pocket on a uniformly heated metal surface.

Fig. 3.

Heat flux in metal heater readjusted to vapor pocket formed (the dotted red lines at $y < 0$). The dotted green lines at $y > 0$ depict the analytic continuation of the lower half-plane. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 4. Vaporization fronts which were initiated at the etched location on the Kanthal resistive strip of $0.4 \text{ mm} \times 0.1 \text{ mm}$ in size at the heat flux of $q_{\infty} = 46.25 \text{ W/cm}^2$ and tracked in the experiments to the left.

Fig. 5. Measured location and velocity of the vaporization front on the Kanthal resistive strip of $0.4 \text{ mm} \times 0.1 \text{ mm}$ in size in the cases of: (a) $q_{\infty} = 46.25 \text{ W/cm}^2$ (b) 50.84 W/cm^2 , and (c) 53.37 W/cm^2 . The experimental data are shown by symbols, and the theoretical predictions by lines.

Fig. 6.

Measured location and velocity of the vaporization front on the $0.5 \text{ mm} \times 0.1 \text{ mm}$ Kanthal resistive strip at the heat flux of $q_{\infty} = 31.60 \text{ W/cm}^2$ experimental data is shown by symbols, and the theoretical predictions by lines.