ABSTRACT

As the Critical Heat Flux (CHF) condition is approached, a thin layer of vapor begins to form between the heated surface and the liquid. The mechanisms leading to the formation of this interface are not clearly understood. The present investigation focuses on obtaining high-speed video images of the liquid-vapor interface and the solid-liquid-vapor contact line. The movement of the interface and the contact line is expected to provide information regarding conditions existing just prior to reaching the CHF.

The experimental setup consists of a droplet impinging on a heated surface in a controlled environment. Two high-speed cameras capable of capturing up to 8000 frames per second are employed to obtain two views of the droplet. The accompanying software is used to determine the velocity and other relevant information regarding the interface. The results are used to discuss the applicability of the CHF and transition boiling models available in literature.

NOMENCLATURE

- $q_c$: critical heat flux, (W/m$^2$)
- $h_{fg}$: heat of vaporization, (J/kg)
- $g$: gravity, (m/s$^2$)
- $D$: initial droplet diameter, (m)
- $d_{max}$: maximum spreading diameter, (m)
- $v$: velocity, (m/s)
- $T$: Temperature, (K)
- $R_s$: surface roughness, (m)
- $We$: Weber Number, $\left( \frac{\rho V^2 D}{\sigma} \right)$

Greek Symbols

- $\rho$: density, (kg/m$^3$)
- $\sigma$: surface tension, (N/m)
- $\theta$: contact angle, (degrees)
- $\beta$: contact angle, (degrees)
- $\phi$: surface inclination angle, (degrees)
- $\mu$: viscosity, (kg/ms)

Subscripts

- $g$: vapor
- $f$: liquid
- $s$: surface
- $w$: water

INTRODUCTION

The initiation of the critical heat flux condition still continues to be an active topic for research. In one of the earliest models, Kutateladze [1,2] proposed that the meanings of bubble generation and departure were lost near the critical heat flux condition, and it was essentially a hydrodynamic phenomenon with the destruction of stability of two-phase flow existing close to the heating surface. Subsequently, Zuber ([3], Chang [4], and Moissis and Berenson [5], among others, developed models based on the interface instability of the rising vapor columns. Haramura and Katto [6] refined an earlier model proposed by...
Katto and Yokoya [7] in which the heat transfer is related to the formation of a macrolayer under a bubble. Small vapor jets formed in the microlayer experience Kelvin-Helmholtz instability leading to coalescence of vapor stems. A detailed survey of the CHF models based on the instability theories is provided by Kandlikar [8].

The vapor recoil has been identified as an important parameter at higher evaporation rates. This is the force exerted by the rapid evaporation from the liquid film at the bubble interface near the contact line region. Sefiane et al. [9] investigated the role of the vapor recoil forces in creating instability at the interface near the contact line region. The rapid evaporation occurring at the base of the meniscus in the contact line region pushes the meniscus surface into the liquid thereby increasing the contact angle. In an earlier paper, Steinchen and Sefiane [10] report a stability analysis and postulate that the vapor recoil force causes an instability at the interface in the contact line region as shown in Fig. 1.

Moosman and Homsy [12] analyzed the meniscus evaporation rates and observed that the evaporative normal flux increased from a very low value in the thick meniscus region to a peak value near the contact line region.

Nikolayev and Beysens [13] postulated that bubble coalescence is not the major cause of the CHF. Citing the experiments by Van Ouwerker [14] and Kenning [15], Nikolayev and Beysens postulated that at CHF, a single dry spot under a bubble begins to spread. They analyzed the transient heat conduction problem in the liquid film and coupled it to a non-dimensional number representing the strength of the vapor recoil force by integrating the vapor recoil force per unit length over the interface. Using these equations, they obtained a qualitative plot for the meniscus profile. The vapor recoil force was thus identified as a triggering phenomenon for CHF. This force acts in the thin belt in the contact line region and is responsible for the change in shape of the meniscus and the contact angle.

Kandlikar [8] proposed that CHF is a localized phenomenon that occurs due to conditions in the immediate vicinity of the heating surface. The liquid-vapor interface at the base of the bubble experiences a large evaporation rate. This results in a vapor recoil effect caused by a momentum change as the liquid evaporates into vapor.

Figure 2 shows a schematic representation of the forces acting on a vapor bubble growing in a liquid over a heated surface. This representation was employed by Kandlikar [8] in developing the CHF model. The forces acting at location A on the contact line between the solid-liquid-vapor phases is of interest. The problem was analyzed by considering 2-D planar model along the center of the bubble. The surface tension forces are $F_{S,1}$ and $F_{S,2}$. The force due to gravitational head is $F_G$, and the force due to evaporating vapor is $F_M$. The force balance results in a limiting value of the vapor momentum force $F_M$. This was then related to the surface heat flux, and the following expression for CHF was obtained.

$$q_c^* = h_p \rho \left[ \left( \frac{1 + \cos \beta}{16} \right) \left( \frac{2 + \pi}{4} \right) (1 + \cos \phi) \cos \theta \right]^{1/2} \left[ \sigma g (\rho - \rho_v) \right]^{1/4}$$

(1)

Where $\beta$ is the receding contact angle and $\phi$ is the angle of orientation of the heater surface with respect to a horizontal upward facing surface. The equation is able to predict the correct parametric trends with respect to contact angle and orientation.

In a recent paper, Kandlikar et al. [16] and Kandlikar and Steinke [17] observed the behavior of liquid droplets as they impinge on a heater surface. High-speed video pictures at a frame rate of 1000 frames per second were taken from side and top views. They noted that the heater temperature affected the shape of the droplet profile near the heater surface. As the
surface temperature increased, critical heat flux was attained, and the movement of the liquid-vapor interface was seen to undergo changes. Figure 3 shows the changes observed in the dynamic advancing and receding contact angles as a function of the heater surface temperature. As the CHF was approached, the receding contact angle jumped to the advancing contact angle. This clearly shows the effect of high evaporation rate on the contact angle near CHF. However, the experiments by Kandlikar and Steinke were conducted with liquid droplets in an atmosphere of air. The present work is carried out to examine the liquid-vapor interface behavior in the atmosphere of water vapor by conducting the experiments in a sealed evacuated chamber.

Figure 3: Dynamic advancing and receding contact angles plotted verses surface temperature, Kandlikar and Steinke [16]

OBJECTIVES OF THE PRESENT STUDY
The present study is aimed at obtaining high-speed photographic video images of liquid-vapor interface as the heater surface temperature approaches the CHF condition. The movement of the interface near the contact line and the changes in the contact angle will be the primary focus of the study. The study is also aimed at evaluating the effect of vapor recoil force on the interface movement in the contact line region.

EXPERIMENTAL SET-UP
The experimental apparatus is designed to allow the experiments to be conducted in a vapor atmosphere. The apparatus consisted of a cylindrical stainless steel vessel with flanges, a droplet delivery system, a leveling stage, a heated copper surface, and a cartridge heater. Figure 4 shows the experimental apparatus.

The vacuum chamber was constructed using stainless steel material. It consisted of a pipe and sealing flanges. The vacuum penetrations were also constructed of stainless steel material. The viewing windows where constructed of ½” thick Lexan polycarbonate.

Figure 4: Schematic of the experimental apparatus. 1) stainless steel vessel, 2) Droplet delivery system, 3) leveling stage, 4) heated copper surface, 5) cartridge heater.

The Lexan was selected for its very low outgassing properties, 0.10% Total Mass Loss (TML) and 0% Collected Volatile Condensable Material (CVCM). A vacuum sealing epoxy was used to seal any penetrations. The heated surface is an electrolytic tough pitch copper C110 (99.9% copper, 0.04% oxygen).

The camera was located outside of the vacuum chamber. It was positioned at a distance 18 centimeters form the heated copper surface. The camera and surface support apparatus were leveled. The Lexan provided an optically transparent viewing window inside the vacuum chamber.

EXPERIMENTAL PROCEDURE
The following procedures was used to prepare the test chamber and the heated test surface. The heated surface was polished using a 1.0 µm alumina slurry. The heated surface has a surface roughness, Ra, value of 0.02 µm (average of five readings). The surface is then thoroughly cleaned several times, using a de-ionized water bath to remove any contaminates. Finally, the copper surface is heated in a vacuum furnace to dry the sample.

First, the chamber was evacuated to a pressure of 17 torr. Degassed, de-ionized water is introduced into the droplet delivery system. The chamber is then filled with water vapor. Once the heater reaches the desired temperature, a single droplet is released to gently lie on the surface.

RESULTS AND DISCUSSION
The inclusion of the force due to vapor momentum was a major departure in Kandlikar’s [8] model from earlier models based on instability criteria in the vapor columns either in the bulk liquid or in the liquid microlayer. The evaporation occurs mainly at the base of the vapor bubble near the contact line region at location A shown in Fig. 2. A more detailed view of this region, referred to as the contact line region, is shown in Fig. 5.
The vapor bubble forms an evaporating meniscus at the base of the bubble on the heated surface at location A in Fig. 5(a). The heat transfer rate and the associated evaporation rate are highest in this contact line region. The evaporating vapor has a higher specific volume than the liquid and exerts a force on the curved thin interface due to a change in momentum caused by evaporation. This force reaches a peak in the contact line region and causes the vapor interface to move under the bulk liquid parallel to the heater surface. These conditions alter the contact angle since the edge of the interface is being pulled away while the entire interface experiences the liquid inertia to any movement. Combined with the depleting liquid inventory in the contact line region, the vapor-liquid interface in the region near A is forced under the bulk liquid. The resulting contact angle is governed by the contact angle hysteresis. The expected shape of the interface after such movement takes place at high heat fluxes is shown in Fig. 5(b).

In the present study, the liquid-vapor interface of an evaporating droplet placed on a hot surface is investigated. This geometry provides an opportunity to observe the interface movement at the outer edge of the droplet contacting the heater surface. The visual study was conducted using a high-speed digital camera. The camera frame rate, shutter speed, aperture, and lighting are adjusted to provide the best possible images. The frame rate is set at 1,000 frames per second. This means that the images presented have a time step of 1 ms. The copper surface appears as dark black base, and the droplet appears in different shades of gray. Figure 6 shows the orientation of the contact angle, contact line, and the coordinate axis.

Figure 5: Liquid-vapor interface at the base of a bubble (a) details of the contact line region, (b) movement of the vapor under the liquid due to evaporating vapor in the contact line region, referred to as the contact line cutback in the present study.

Figure 6: Contact line at the bubble base.

The first example of Contact Line Cutback is seen in Fig. 7. A droplet of 2.8 mm initial diameter impacts the copper surface from a distance of about 12 mm. The droplet is at an initial temperature of 22°C. The surface is at a steady state temperature of 150°C prior to impact. The focus should be on the left hand side of the droplet. The contact angle is around 120 degrees, and the interface in the contact line region is experiencing a cutback phenomenon. In Fig. 7B, the contact line has moved considerably under the droplet. However, the motion of the interface is somewhat reversed in frame (C), because the surface temperature is not high enough to support the rapid dryout, and the contact angle is seen to decrease.

Figure 7: Contact Line Cutback upon impact. The left side of this droplet is exhibiting the cutback phenomenon. The event time is: A) 0.0 ms, B) 1.0 ms, C) 2.0 ms, D) 3.0 ms, E) 4.0 ms, and F) 5.0 ms. $T_w = 22°C$, $T_s = 150°C$, $D = 2.8 mm$. 
The vapor resumes to cut back under the liquid Fig. 7D, but once again, its motion is stopped in Fig. 7E. The contact angle at the left edge of the droplet is again changed to a higher value as the cutback phenomenon resumes in Fig. 7F. The main reason why the vapor cutback is not complete under the droplet is that the surface temperature is not high enough. However, at very high surface temperatures, the phenomenon is too rapid to obtain clear images.

Another example is found in Fig. 8. In this case, a droplet is boiling on the heater surface. The droplet has an initial diameter of 2.8 mm and an initial temperature of 22°C. The copper surface has an initial temperature of 150°C. The right side of the droplet shows the area of interest. In Fig. 8A, the contact line has a high contact angle, and it is rapidly moving underneath the droplet. This causes a good portion of the droplet to be left unsupported. The unsupported liquid moves upward, away from the heated surface. This is due to the force created by the rapidly evaporating water from below. Figure 8C shows the contact line region returning to a quasi-stable shape. This shape is much like the one shown in Fig. 7E. The contact angle is decreasing in the subsequent frames, and the liquid is covering back the heated surface underneath the droplet.

The contact line cutback can also be seen in Fig. 9. In this case, the droplet has impinged upon the surface and is boiling upon the surface. The initial droplet diameter is 2.8 mm and the initial surface temperature is 150°C. Again, the focus is on the left edge of the droplet. The event begins in Fig. 9A. The next frame shows the contact line is forced to move underneath the droplet. The contact angle is changed from about 75 degrees in Fig. 9A to about 90 degrees in Fig. 9B as the droplet experiences the cutback phenomenon. The vapor film has moved considerably under the liquid droplet in Fig. 9F.

Figure 10 illustrates another condition when contact line cutback occurs. In this case, the droplet has impacted and has gone through several advancing and recoiling cycles. It has also been levitated above the surface due to film boiling. The figure shows what occurs when the droplet is returning to the surface after levitation. The event begins in Fig. 10A immediately prior to the contact with the heated surface. A contact is established in Fig. 10B. In Fig. 10C, the contact line rapidly moves out from under the droplet on both sides. A spray of water can be seen coming from beneath the droplet. This rapid evaporation causes the entire droplet to move upward, away from the heated surface. The rapid evaporation and the resulting vapor cause the droplet to continue its upward motion in Figs. 10D-F.

Figure 9: Contact Line Cutback during transition boiling on the left side of the droplet. The event time is: A) 0.0 ms, B) 1.0 ms, C) 2.0 ms, D) 3.0 ms, E) 4.0 ms, and F) 5.0 ms. Tw = 22°C, Ts = 150°C, D = 2.8mm.

Figure 10: Contact line cutback after droplet levitation. The droplet is exhibiting the cutback phenomenon. The elapsed time from the moment of initial contact with the heater surface is: A) 0.0 ms, B) 1.0 ms, C) 2.0 ms, D) 3.0 ms, E) 4.0 ms, and F) 5.0 ms. Tw = 22°C, Ts = 150°C, D = 2.8mm.
The droplet is exhibiting the cutback phenomenon. The event time is: A) 0.0 ms, B) 1.0 ms, C) 2.0 ms, D) 3.0 ms. 

The same event that was pictured in Fig. 10 is shown in Fig. 11. However, the surface temperature is now at a higher value, 175°C. It is the same situation as for Fig. 10. The droplet has impacted and gone through several advancing and recoiling cycles. It has also been levitated above the surface due to film boiling. The figure shows what occurs when the droplet is returning to the surface after levitation. The event begins in Fig. 11A. A spray of water vapor can be seen coming from beneath the droplet at an increased time step. The event is occurring at a faster rate than in Fig. 10. The burst of the vapor and liquid is caused by a vapor bubble which forms somewhere in the center of the droplet as it contacts the heater surface. The contact line, not seen in any picture here, is believed to push the contact line region away in the radial direction at the base, leading to the explosive burst of liquid vapor mixture. The resulting vertical force from the expanding bubble cause the droplet to fly back in its upward trajectory. Figure 10D shows the droplet continuing to propel upward.

CONCLUSIONS

The movement of the contact line region under a liquid droplet impinging on a hot surface is investigated. The contact line region phenomena at the outer edge of the droplet base is expected to provide insight into the contact line region in a vapor bubble growing under a pool of liquid on a heated surface. The movement of the interface in the contact line region under the liquid is called as the Contact Line Cutback. The following conclusions are drawn from the visual observations of the high speed video images of the liquid droplet.

- The cutback phenomenon occurs at several different stages during the droplet impingement cycle. Figure 7 demonstrates the occurrence of the cutback during the first advancing of the droplet just after impingement. Figures 8 and 9 shows it happening while the droplet has an extended contact with the surface. Figures 10 and 11 demonstrate the occurrence when the droplet returns to the surface after levitation. This phenomena causes the liquid to be drawn away from the heater surface with an interspersed vapor layer, a condition that leads to CHF and transition boiling.
- An increase in surface temperature seems to provide an increase in the evaporation rate. In turn, this allows the process to increase in speed.

The present study supports the model developed by Kandlikar [8], in which the rapid evaporation of the interface in the contact line region is considered to initiate the CHF condition. The contact line cutback phenomenon can be attributed to the changing momentum and force imbalance caused by the rapid evaporation of the liquid in the contact line region. Future work should include a further quantification on the conditions required for vapor cutback. In addition, high-resolution optics in conjunction with the high speed imaging are recommended to observe the contact line region in greater detail.

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REFERENCES


