AIP Applied Physics Letters

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Citation: Applied Physics Letters **86**, 134107 (2005); doi: 10.1063/1.1873053

View online: http://dx.doi.org/10.1063/1.1873053

View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/86/13?ver=pdfcov

Published by the AIP Publishing

APPLIED PHYSICS LETTERS **86**, 134107 (2005)

Direct observation of a liquid film under a vapor environment in a pool boiling using a nanofluid

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(Received 22 October 2004; accepted 10 January 2005; published online 24 March 2005)

The existence of a liquid film separating a vapor bubble from a heated solid surface is confirmed using a nanofluid. The existence of such a liquid film had been a theoretical premise of the critical heat flux mechanism, significantly difficult to verify through experimental observations. Here, we show that a liquid film under a massive vapor bubble adheres to a heated solid surface. The liquid film comes into being trapped in a dynamic coalescence environment of nucleate bubbles, which grow and depart continuously from the heated surface. In its dryout process, the liquid film displays vapor "holes" originating from the rupture of discrete nucleating bubbles. The dryout process of the liquid film can be understood from the vaporization of rims of the holes and of smooth film region. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1873053]

Boiling is a phenomenon of nature whereby the application of heat changes a liquid to a vapor; during the process of this change, bubbles appear in the hot liquid. The practical application of boiling by humans is probably one of the most ancient arts, dating back to the days of primitive humans,[1] and still new applications for boiling are currently being found. For instance, boiling has important modern applications for macroscopic heat transfer exchangers, such as those in nuclear and fossil power plants, and for microscopic heat transfer devices, such as heat pipes and microchannels for cooling electronic chips. In addition, the core technology that made a commercial success of thermal ink-jet printers is based on the application of boiling bubbles, which propel tiny ink droplets through the openings of an ink cartridge.[2] The use of boiling is limited by critical heat flux which is characterized by both its highest efficient heat transport capability and the initiation of surface damage caused by suddenly deteriorating heat transfer. For instance, damage can be directly related to the physical burnout of the materials of a heat exchanger. However, the physical mechanism of this limitation has not been understood clearly.

To explain the mechanism behind the boiling limitation, there are two classical hypotheses: one hypothesis considers the obstructions of heat transfer due to vapor masses anchored on the heated surface, and the other hypothesis postulates that the limitation is due to the existence of a limit in the state of the fluid system; for example, there are geometrical theories based on critical bubble spacing near the heated surface and hydrodynamic ones based on the instability of the interface between liquid and vapor.

However, visual observations have not confirmed either hypothesis. In relation to the mechanisms, there is a general consensus that fully developed nucleate boiling on a heated solid surface is characterized by the existence of a liquid film on the heated solid surface.[3] The occurrence of the boiling limitation, the so-called critical heat flux (CHF) has been linked closely to the behavior of the liquid film. This liquid film is generally referred to as the "thin liquid layer" or the "macrolayer" to distinguish it from the microlayer that exists under the base of discrete nucleating bubbles.[3] The question to be answered is whether a stable thin liquid layer under a vapor boiling environment could actually exist. If so, what precisely is the role of such a liquid film in relation to the boiling limitation? Reliable answers will depend on direct experimental observations.

Currently, there has been no direct observation of the liquid layer. For example, the investigations of Gaertner and Westwater[4] and Kirby and Westwater[5] have supplied only indirect indications of the existence of such a liquid layer. Numerous subsequent studies have failed to provide a direct confirmation of a stable thin liquid layer under a vapor boiling environment. In 1977, Yu and Mesler[6] offered a hypothesis of the existence of the layer, as illustrated in Fig. 1(a). Katto and Yokoya[7] demonstrated the importance of Yu and Mesler's hypothesis; they used it to show that it is possible to approach the very complex boiling limitation phenomenon with a relatively simple liquid layer evaporation mechanism, using a simple energy balance equation, such as

$$qt_h = \delta\rho_f h_{fg}\left[1 - \frac{A_v}{A_w}\right]. \tag{1}$$

As a result, the Katto and Yokoya hypothesis came to be accepted during the last half century, though actual proof of the layer has continued to elude many investigators.

The current work proposes a new method to prove the existence of the layer. Our method involves two new ideas. The first idea is that a direct observation of the layer can be achieved under an environment in which the liquid phase is distinguished clearly from the vapor phase. We use a nanofluid as a colored fluid in order to distinguish between the liquid phase and the vapor phase in a complex boiling environment. We chose alumina nanofluid with white color nanoparticles for this purpose. The fluids are prepared by dispers-

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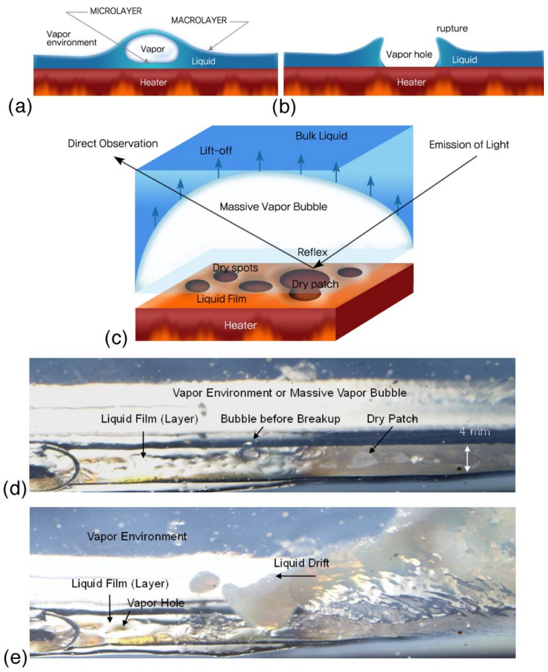

FIG. 1. (Color online) Liquid film structure. (a) Conventional illustration of hypothesis for liquid film structure. (b) New illustration for vapor hole being formed by spontaneous breakup (or rupture) of a bubble. (c) New ideas for the direct observation. A nanofluid is used as a dyed-water. Diagonal view is used for the experimental observation. Dry spot means a dried area below a discrete bubble during its formation and vapor hole after bubble's breakup. (d) Evidence of the liquid film. A bubble just before spontaneous breakup is shown in the liquid film. (e) Liquid drift based on the liquid film into the vapor environment. Images (d) and (e) in Fig. 1 by a diagonal view show phenomena confirming the existence of a liquid film under a massive vapor bubble or vapor environment. Also, the images show a part (with ~60 mm length) of the direct Joule heating plate (heater) measured 4 mm (width) ×100 mm (length).

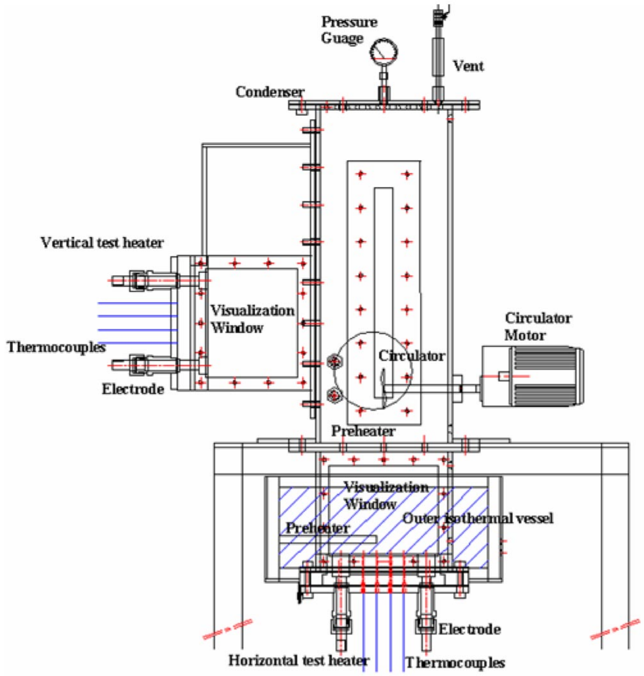

FIG. 2. (Color online) The schematic of the nanofluid pool boiling test facility.

ing alumina nanoparticles into water as a base fluid.[8,9] Transmission electron microscopy (TEM) reveals alumina nanoparticles as having a spherical shape, with a normal size ranging from 15 nm to 124 nm (a 47 nm average diameter).

The second idea is that a direct observation of the layer can be achieved under a new view of visualization. Actually, we can divide the experimental observations and hypotheses into the three traditional groups of a top-down approach, a bottom-up approach, and a lateral-inside approach. One new diagonal-inside approach is newly introduced in the present work. Figure 1(c) shows the new two ideas: the white colored fluid and the new view of visualization.

All tests for the direct observation were performed using a digital camera system in pool boiling under atmospheric pressure. The pool boiling test facility is shown in Fig. 2. A test plane heater with copper electrodes is heated by a dc power supply. The boiling surface of the test plane heaters is $4 \times 100\ \mathrm{mm}^2$ rectangular with a depth of 1.9 mm.

Boiling and the boiling limitation are phenomena characterized by periodical processes or intermittent processes. A typical example of the generation process of a liquid film (Fig. 3) at a high heat flux level shows that the generation proceeds through the formation of nucleate bubbles resulting in the growth of a massive vapor bubble. Liquid both internally trapped by means of both lateral and vertical coalescence of nucleate bubbles and externally supplied through triple phase line spreads on a solid surface while the bubbles form a massive vapor bubble due to the film itself consumption. In the other words, individual bubbles may lie above a thin liquid layer on a heater surface and the growth of the bubbles proceeds through the evaporation of the thin liquid. While spreading, some vapor holes are displayed inside the film as decreasing small holes. Vapor holes originate from the rupture of discrete individual nucleating bubbles. Later, the thin film is in a typical dryout stage, with evaporation in the rims of the vapor holes and in the overall liquid film–vapor interface. The film breaks up into local liquid fragments [Fig. 4(a)]. In particular, the size of each vapor hole increases to contain a much larger dry area with evaporation around the rim in dryout process. Also, the vapor holes merge with neighboring holes, resulting in a large dry area. After a few msec, the surface is covered by only vapor or small liquid droplets, in place of the liquid.

With a further increase in heat flux level, the liquid film dries out completely. Then, in accordance with the periodical process of boiling, a new liquid film forms, by means of the aforementioned trapping in the boiling, while the bulk liquid is again supplied near the surface and so the life and death of liquid film are repeated.

Although liquid film dried out fully, the boiling limitation does not occur yet. Actually, at the boiling limitation, we can observe that the local part of the surface wetted by the liquid film does not rewet, as shown in Fig. 4(c). A limiting boundary between the nonwetting hot surface and the wetting cold surface is shown in a photo. Over time, the boundary expands to the wetting area with evaporation around the holes. The dryout of the part continues for much longer than for one of the periodical process. In contrast, in a lower heat flux level apart from boiling limitation, a liquid film is sufficiently thick. Figure 4(c) shows the time reconstruction of statistically representative dryout processes. The figure shows that the surface is not rewetted, which leads to burnout of metal failure in boiling limitation, as shown in Fig. 4(c).

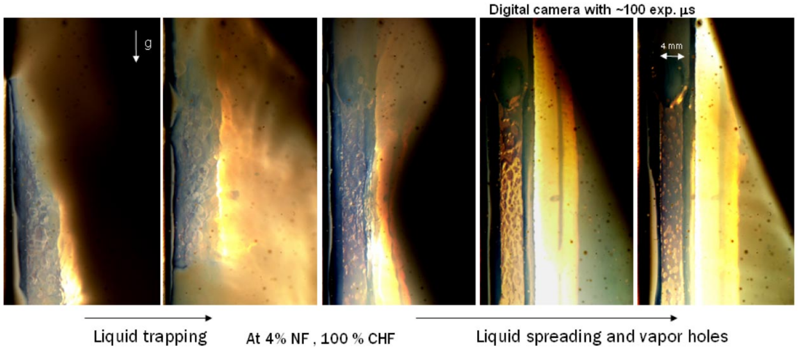

FIG. 3. (Color online) Liquid film formation process: Liquid trapped by nucleate bubbles in a expanding vapor environment from 4 vol % Al_2O_3–water nanofluid at CHF is shown. Nucleate bubbles disappear little by little and a liquid region with small holes begins to appear. Liquid disturbed in the process spreads on the surface. The third image shows a typical wave interface by Taylor and Helmholtz instability theories. All images are taken by a single-lens reflex digital camera with a Macrolens system and ~110 μs exposure time.

Special attention should be given to the vapor holes in the liquid film. In Fig. 4(b), we present a typical hole-liquid structure. In the vapor environment, large vapor holes are seen inside the liquid film, whereas nucleate bubbles are seen just before the rupture for forming liquid film region, as shown in the lower part of the figure. The liquid dries out with the expansion of the dried regions or the vapor holes due to evaporation from the rims of vapor holes. This resembles a dewetting process[10] which is characterized by holes and the motion of liquid rim apparently. The size and distribution of these vapor holes originally depends on the distribution of nucleation sites, whereas those of the observed vapor holes depend on the observation time in a period of the process.

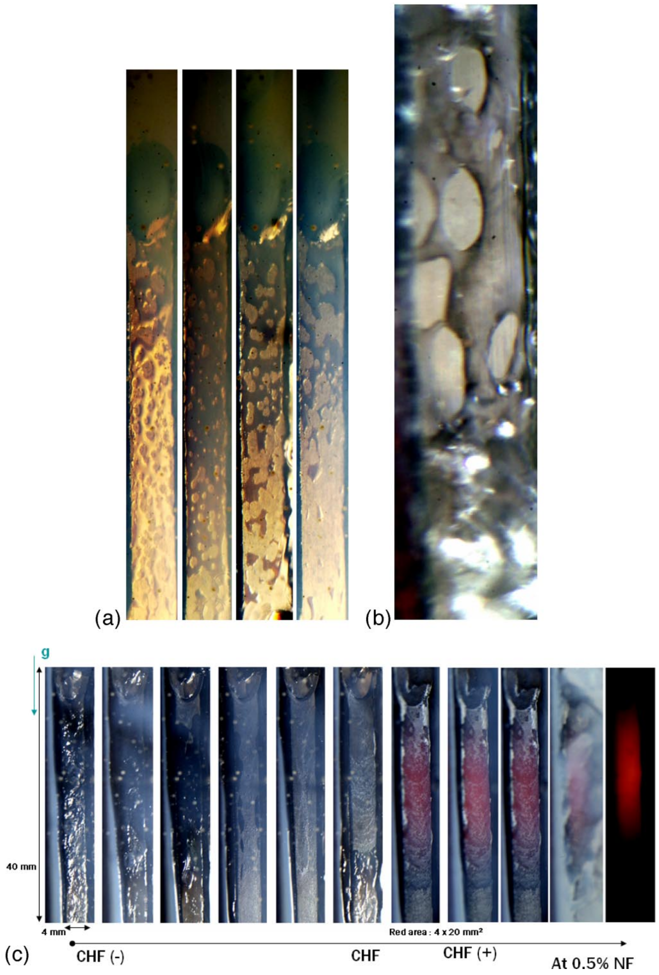

FIG. 4. (Color online) Liquid film dryout process: (a) Time evolution of dryout of the liquid film from 4 vol % Al_2O_3–water nanofluid at CHF. The liquid spreading occurs after its trapping and the dryout process of a liquid film proceeds with its evaporation. In the top of an image, there is a nonheating part of the surface resulting in relative thicker interleaved liquid film without any dried area. (b) Magnification of the liquid film–vapor holes structure. (c) The burn-out (critical heat flux) phenomenon due to dryout of the liquid film. Entirely dried and nonwettable surface of the heater glowed in CHF (+). Thus, the surface must not be rewetted despite liquid resupply as shown in the image in front of the last. The last image of (c) shows a glowing surface of the heater in the dark.

Several questions remain concerning the observation: How thick is the trapped liquid layer? What determines the thickness of the layer? Why does nonwetting of liquid in boiling limitation occur?

The typical thickness of this layer is predicted to have a range from 50 to 500 μm for water on a flat horizontal surface, depending on the heat flux. There are many hypotheses regarding the factors that determine the thickness; such factors could include Helmholtz instability, the contact angle, or the nucleation site density.[3] The mechanism of the boiling limitation is that periodical wetting and dryout cause the rise of average temperature, and then the rise of average temperature prevents the wetting during the period of liquid resupply. Therefore, according to Newton's cooling law of

$$q = h(T_w - T_f), \qquad (2)$$

the sudden falling of the heat transfer coefficient, due to the conversion of a liquid–solid interface to a vapor–solid interface, causes the sudden rising of the wall temperature, leading to a melt down of the wall or to burn-out.

The experimental observations of this study will contribute to the ability of heat transfer community to provide actual depictions of the liquid film and the structure.

The authors thank Professor H.C. No and Dr. D.W. Lee from KAIST, and Dr. S.Y. Chun, Dr. S.K. Moon, and Dr. S.H. Kim from KAERI for helpful discussions. This research was supported by Korea Atomic Energy Research Institute and Korea Ministry of Science and Technology.

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