

# Nanofluid Application : Liquid Sublayer Structure and Heat Transfer Mechanism

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## 1. Introduction

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. 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.

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 [1]. 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 [1]. 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. 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 [2] offered a hypothesis of the existence of the layer, as illustrated in Figure 1.



Figure 1. illustration of liquid sublayer structure [7]

Katto and Yokoya [3] demonstrated the importance of Yu and Mesler’s hypothesis; they used it to show that it is possible to approach the very complicated boiling limitation phenomenon with a relatively simple liquid

layer evaporation mechanism, using a simple energy balance equation, such as

$$qt_h = \delta\rho_f h_{fg} \left[ 1 - \frac{A_v}{A_w} \right] \quad (1)$$

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.

## 2. Methods and Results

We use a nanofluid as a colored fluid in order to distinguish between the liquid phase and the vapor phase in a complicated boiling environment. We chose alumina nanofluid with white color nanoparticles for this purpose. The fluids are prepared by dispersing alumina nanoparticles into water as a base fluid [4][5]. 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 avg. diameter).

All tests for the direct observation were performed using a digital camera system in pool boiling under atmospheric pressure. A test plane heater with copper electrodes is heated by a DC power supply. The boiling surface of the test plane heaters is 4 x 100 mm<sup>2</sup> 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 at a high heat flux level in Figure 2 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. 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. 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.

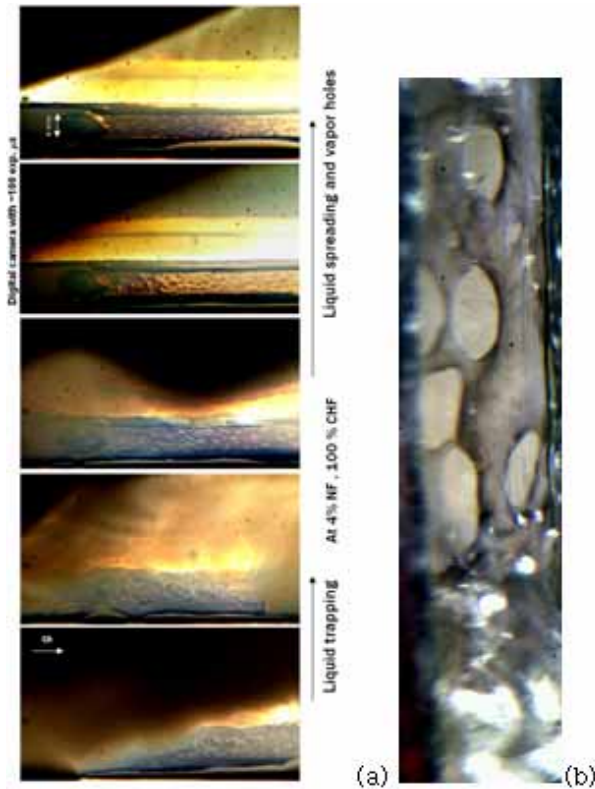


Figure 2. Life and death of liquid sublayer [7]

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.

Special attention should be given to the vapor holes in the liquid film. In Figure 2 (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 [6] 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.

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

$$q = h(T_w - T_f) \quad (2)$$

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 as shown in Figure 3.

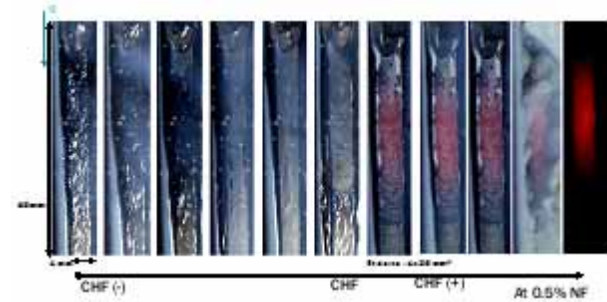


Figure 3. Burn-out due to critical heat flux [7]

### 3. Conclusion

We have reported here on the existence of a liquid film under a vapor environment. 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. This, in turn, will lead to a variety of practical applications for devices, such as micro- and macro- heat exchangers, MEMS heat transport devices, and actuators, as well as to a design for the enhancement of heat transfer.

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