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An experimental investigation on bubble dynamics and boiling crisis in liquid films

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ABSTRACT

This paper presents an experimental study of boiling and boiling crisis in a liquid film on a heater surface. The critical heat flux (CHF) values obtained in the present experiment mirror that of pool boiling, irrespective of initial liquid film thickness and liquid supply rate in the liquid film boiling case. This observation reinforces to the "scale separation" concept that high-heat-flux boiling and burnout are governed by micro-hydrodynamics in the liquid film on the heater surface. In addition to the CHF data, evolutions of bubbles and dry spots in the boiling liquid film are captured by means of high-speed high-resolution video camera. The dry spots were observed over surface heat flux ranging from 0.3 MW/m^2 to CHF, typically covering an area less than 10% of the heater surface. Three types of dry spot evolution are observed: (1) under the low heat flux, dry spots are rewetted by receding water dam upon rupture of corresponding bubbles; (2) as the heat flux reaches 1.25 MW/m^2, dry spots rewetting is additionally aided by liquid flow driven by growth of bubbles nucleated in the vicinity; (3) upon approaching the CHF, dry spot(s) cannot be rewetted anymore and expand laterally, leading to boiling crisis (burnout of the heater surface). The richness of observations and characterization of micro-hydrodynamics in the present study further demonstrates that observations and measurements on boiling liquid films provide a paramount window for investigation and understanding of physical mechanisms of boiling and boiling crisis.

1. Introduction

Thermal management in power-intensive equipment presents an increasing challenge, often requiring removal of heat fluxes in the range from 1 to 30 MW/m^2, or even higher, over sizable areas of several square centimeters or much larger. For such systems, nucleate boiling can provide a highly efficient cooling mechanism. The use of nucleate boiling for heat removal is limited by boiling crisis associated with departure from nucleate boiling (DNB) at so-called critical heat flux (CHF). As the boiling surface dries out, the heater's temperature rises rapidly, leading to system's melting and destruction (hence "burnout"). Despite their prominent place in heat-transfer textbooks, mechanisms of boiling heat transfer and boiling crisis remain poorly understood. Because of its importance for determining safety margin in high-power-density engineered systems, nucleate boiling coolability limit continues to be a fascinating research topic even after several decades of intensive experimental, theoretical, and computational investigations.

On the experimental side, the study of boiling is impeded by the presence of multiple liquid–vapor interfaces, dynamically evolving and covering a broad range of length scales that extends down to the molecular level. Of importance are mechanisms of heat transfer which occur at the heater's surface and whose diagnosis had long been limited to integral or point measurements, (i.e., heater surface-averaged heat flux and temperature, and local temperature).

On the theoretical side, even though elementary and reduced processes in boiling systems, e.g. nucleation, bubble dynamics, turbulence have been subjects of study for centuries, much remains elusive about boiling as a whole. Particularly at high heat fluxes, the reduced processes become tightly coupled, making high-heat-flux boiling a formidably complex system. This complexity present intellectual challenges and motivations for fundamental research in multiphase fluid dynamics and heat transfer.

On the practical side, a major objective of boiling heat transfer research is to enable a mechanistic understanding, model-based prediction, control and enhancement of nucleate boiling's coolability limit.

Over the years, mechanisms that govern boiling crisis had been sought in hydrodynamics, as manifested through dependence of CHF on gravitational acceleration, fluid density, and surface tension

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[1]. Research in the past built around a notion that the cause of DNB is insufficient liquid supply to the heater surface due to the repulsive effect of vapor leaving the surface [2]. This so-called hydrodynamic origin of burnout has led to several conceptual models that were translated to methods to calculate CHF over a whole range of conditions spanning from pool to forced convection boiling [3].

As early as 1950s, researchers reported boiling data that appeared to be outliers to the hydrodynamic theory. More systematically over the last two decades, the research provides a growing body of evidences that microphysics factors such as surface materials/chemistry/morphology, and coolant chemistry (including nanoparticles) play an important – even dominant – role in nucleate boiling and burnout. Remarkable discoveries are made in recent studies that nano/micro-structured and wettability-controlled surfaces offer potential for a substantial enhancement of CHF [4–9]. The physics at microscopic scales, in combination with extraordinary advances in diagnostics, theory and computation, present an unprecedented opportunity for boiling research [10]. However, bringing these promises to engineering practice has been hampered by complexity in interpreting and reconciling a large amount of heterogeneous, complex and seemingly conflicting data obtained from boiling simulations and experiments under a variety and variability of conditions.

Using a combination of diagnostics (infrared thermometry, X-ray radiography, video imaging) in an innovative experimental concept called BETA, Theofanous et al. [11,12] identified fundamental deficiencies in the hydrodynamic models of boiling crisis in pool boiling on horizontal heaters, that burnout is far from being hydrodynamically limited. The insights also led to conceptualization of a scales separation phenomenon that in high heat-flux boiling, dynamics of liquid film and heat transfer on the heater surface is autonomous, as they are separated, by a vapor blanket, from chaotic, churning two-phase bulk flow. Given the scales separation, mechanisms that govern the boiling crisis should be sought within the evaporating liquid film's micro-hydrodynamics, and not limited by the bulk flow macro-hydrodynamics.

During the past decade, a number of analytical and computational models [13–17] for boiling heat transfer were developed to investigate micro-hydrodynamics of near-wall liquid microlayers or macrolayers. While definitions of the layers have been fuzzy and at times intertwined, the thickness of these layers is estimated to range from several micrometers to several hundreds of micrometer [18–23]. Important steps were made in developing new experimental concepts and diagnostic techniques to enable characterization of macrolayer and bubble dynamics on a heater surface. This includes transparent heaters that enable visualization of boiling processes through the heater [24–30].

In the present study, boiling mechanisms are investigated on a thin liquid layer, to facilitate visualization and measurement of liquid layer both from the top and through the bottom. It builds on the scale separation concept derived from the BETA program that high heat-flux boiling and burnout are governed by micro-hydrodynamics. The experimental concept was first advanced in BETA-B experiment: the film micro-hydrodynamics is visualized by a high-speed video camera (top view) synchronized with the IR imaging (bottom view), without losing the key physics of boiling process [31].

The present study advances the BETA-B experimental concept by adding novel instruments for quantification of liquid film thickness and dynamics, while following the same principle for design and fabrication of heaters i.e., using nanometers titanium coating on a glass sheet as the heater. The unique feature is to measure the liquid film thickness evolution by a confocal optical sensor [32] and to capture bubble dynamics by high-speed shadow photography. The experimentation enables us to investigate the influences of liquid film thickness on critical heat flux (CHF) of boiling, and in a way to verify the 'scale separation' hypothesis. At the same time, the high-speed visual observations directly on the liquid film provide new insights on bubble dynamics and dry spot evolution over the heater surface.

2. Experimental setup

2.1. Test facility

The test facility, as shown in Fig. 1, is designed and developed in such a way that provides a platform for performing boiling tests in a liquid film with high stability and accuracy of operation and measurement. The facility consists of an optical table, liquid supply and temperature control system, power supply and heating system, high-speed visual system, confocal optical sensor system, one-dimensional linear manipulator, three-dimensional micro-manipulator and its control system, lighting system, and a test section for boiling on a titanium film heater coated on a piece of glass sheet. The optical table provides the required vibration isolation for both the test section and the instrumentation mounted on the platform. Deionized water is pre-heated in a stainless steel water tank by two band heaters to a desired temperature which is maintained with a temperature controller; the hot water (95 ± 2 °C) is then supplied to the test section through a micro pump capable of accurate flowrate control.

2.2. Test sections

Two kinds of tests were performed in the present study. One is liquid film boiling (Fig. 2(a)) and the other is pool boiling (Fig. 2(b)). The heaters used in both tests are the same. The fabrication of the heater is as follows: on a piece of 1-mm-thick quartz glass (40 mm × 30 mm), first sputtering a 150-nm-thick titanium film to an area of 40 mm × 8 mm, then sputtering two 300-nm-thick gold films (16 mm × 8 mm each) over the titanium film with 8 mm gap. As a result, an 8 mm × 8 mm area of titanium film is formed in the middle of the glass sheet as the heating zone for boiling while the gold coatings are connected to the electrodes. Fig. 3 shows the SEM image of the titanium film which is a nanometer level smooth and uniform surface. Under the heating zone, a micro T-type thermocouple is embedded and fixed by silver glue into an artificial cylindrical hole with 0.5 mm depth and 0.3 mm radius on the downward surface of the quartz glass to measure the wall temperature. A Teflon structure is manufactured to hold the film heater and then fixed onto the optical table. The supporting structure can be regulated to reach a horizontal orientation of the heater surface.

Fig. 2(a) is the test section for the boiling experiments in the liquid film. The gold films of the heater are tightly connected to two gold blocks (30 mm × 6 mm × 3 mm) serving as the electrodes to a DC power supply as well as the boundaries of water film formation. The open channel bounding the liquid film between the electrodes is 16 mm wide and 30 mm long, with the heating zone situated at its center zone. Saturated water is supplied to the channel from one side whose end is sealed by a 3-mm-tall glass dam to direct water flow in only one direction toward the other side where a height-adjustable glass sheet is used to regulate the water layer thickness. When the height of the glass sheet is set to be 1 mm, an adiabatic liquid film above the heating zone in the channel will achieve a balance condition with a relatively flat surface, and its thickness depends on the flow rate of the water supply. The de-ionized water is preheated to desired temperature in the water tank, and delivered to the test section by the micro pump which has accurate step control with the resolution of 0.0142 ml/s. The tube