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Dynamics of a thin liquid film under shearing force and thermal influences

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ABSTRACT

Study of liquid film dynamics promotes understanding the critical heat flux (CHF) of boiling heat transfer, which occurs as the liquid layers (micro-layer and macro-layer) near the heater wall lose their integrity. Since the measurement at micro-scale is a challenge, and further complicated by the chaotic nature of the boiling process, profound knowledge on the thin liquid film dynamics is not well documented in the existing literature. In the present paper, we employ a confocal optical sensor system to study the dynamics and the integrity of a thin liquid film sheared by the co-flowing air from above and heated from below in a horizontal aluminum channel. The results indicate that the entrainment governs the liquid film thinning process under adiabatic or lower heat flux conditions, whereas the evaporation becomes more pronounced in a higher heat flux system. The detailed evolution of liquid film is discussed. Based on our experimental observations, the critical film thickness of an integral film is related to the condition of the heating surface and the heat flux. For a specific surface, the critical film thickness remains constant under a defined heat flux and increases with the increasing heat flux. A spectrum analysis is also implemented to analyze the film instability. It is concluded that the heat flux is the dominant factor to govern the film instability compared with the effect of differential velocities of gas and liquid flow.

1. Introduction

A thin liquid film spreading over and evaporating on a solid surface is encountered in many engineering applications that involve processes such as spray cooling, heating, coating, cleaning and lubrication. In most cases, the stability and integrity of the liquid film on the heating surface is desired to avoid performance deterioration and physical destruction of the devices. Note that the performance of a boiling device is bounded by the critical heat flux (CHF), which is thus an important parameter for system design and operation [1]. If the liquid film rupture occurs in boiling heat transfer, for instance, the heat transfer coefficient may be considerably reduced and it will lead to the burnout (dryout) which is a threat to the equipment safety.

So far, an extensive research has been carried out in the investigation the liquid film dynamics and integrity. The minimum thickness of an integral liquid film is of special interest since it is related to film rupture. For adiabatic conditions, the minimum thickness of the film flowing down a vertical or inclined solid surface can be predicted theoretically according to force balance or minimum total energy criteria [2–7], as well as a horizontal liquid film by free energy theory [8,9]. Oron et al. [10] provided a comprehensive review of the multifaceted subject of thin film dynamics modeling. Based on the long wave theory, they presented a unified mathematical system to predict the long-scale evolution of thin liquid films. The set of mathematical evolution equations has its root in the work of Burelbach et al. [11], taking into account the influential factors such as van der Waal forces, surface tension, gravity, thermo-capillary, mass loss and vapor recoil force. Later, Craster and Matar [12] also presented a comprehensive review of the work carried out on thin film flows. As pointed out by Oron et al. [10], there is a clear need for careful experimental investigations to verify phenomena and to give data that can be used to test the theories, and they claimed their review paper stands as a call for such experiments. Remarkably, there are few data for film rupture on a horizontal surface under non-adiabatic conditions which is important to boiling heat transfer and boiling crisis.

Additionally, most of the published modeling and numerical studies for boiling heat transfer concentrate on the near-wall liquid

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Nomenclature

f	frequency (Hz)
M_l	liquid mass flow rate (g/s)
q	heat flux (kW/m^2)
t	Time (s)
u_m	mixture velocity (m/s)
u_{sg}	gas superficial velocity (m/s)
u_{sl}	liquid superficial velocity (m/s)
x	axial distance (mm)

Greek letters

δ	film thickness (mm)

Subscripts

g	gas
l	liquid

layers (micro/macro-layer) with the thickness estimated to range from several to hundred micrometers [13–17]. However, there is a dearth of data on the direct measurement of such near-wall liquid layers. This is probably due to the fact that the measurement at micro-scale is a challenge, and further complicated by the traditional experimental setups (e.g. Pool boiling with heater block) and the chaotic nature of boiling process which all impede direct observation and measurement of thin liquid films, especially under high heat-flux conditions.

Theofanous et al. [18,19] proposed a "scales-separation" phenomenon which indicates that high heat-flux boiling and boiling crisis is dominated by micro-hydrodynamics of liquid microlayer on the heater surface. More specifically, for a given surface condition and coolant chemistry, boiling crisis can be treated as a hydrodynamic phenomenon, and there exist two hydrodynamic scales: an external one and an internal one. However, boiling crisis in pool boiling is irrelevant to the external-scale hydrodynamics. Note that the "scales-separation" phenomenon can also be applied to flow boiling [20]. This provides the rationale to perform the BETA-B boiling experiment [21] on a thin liquid film so that the micro-hydrodynamics of the film was visualized directly by a high-speed video camera synchronized with the IR imaging, without losing the key physics of boiling. To take one step forward, Gong et al. [22,23] developed an experimental method for the diagnosis of liquid film dynamics and investigated the stability and rupture of evaporating liquid films on different heater surfaces under boiling conditions from low heat fluxes to high fluxes [24–26]. The data were then applied in the modeling and simulation of liquid film dynamics [27]. Since previous studies were oriented to pool boiling, there is a clear need to advance the developed experimentation to flow boiling so that the research is applicable to boiling water reactors. Note that the flow boiling features a liquid film driven by shear forces of vapor flow in the mainstream. The shear force not only affects the instability of the micro-layer, but also forces the liquid in the micro-layer to spread into the dry areas. Generally, the interfacial waves on the liquid film is believed to trigger the dryout in flow boiling [28]. However, the experimental quantification of such thin liquid films and their dynamics is not straightforward. Essentially, more experimental data and in-depth analysis are required to investigate the film rupture.

The present study calls into question the effects of gas shearing and evaporation on the dynamics of a thin liquid film. We develop a confocal optical sensor system for a rapidly varied liquid film and try to evaluate the factors and properties which govern film dynamics, stability and rupture. We discuss the effects of entrainment and evaporation on liquid film evolution. We also analyze the effects of different parameters (e.g. gas and liquid flow rate, heat flux, etc.) on the critical film thickness. Based on the spectrum analysis, we discuss the film instability under various flow conditions, providing insights into the dynamics of a thin liquid film.

2. Experimental system and method

2.1. Test facility

Fig. 1 shows the schematic of the test facility which mainly consists of water and air supply systems, a heating system, a test section as well as a measurement system. The test section is a rectangular channel made of aluminum with the length of 180 mm, the width of 8 mm and the height of 12 mm, as seen in Fig. 2. In order to isolate the vibration, the test facility is fixed on an optical table which also serves as an operating platform to fix the test section horizontally. The surface of the test channel has the properties of 0.293 Ra/μm for roughness and 68° for contact angle. For the purpose of forming a stratified flow with minimum entrance effect, a water-air inlet section is carefully designed to make water and air flow into the test section in parallel.

The main difficulties for the dynamics of the thin liquid film measurement are the film's small scale and rapid evolution, as well as randomness of nucleation and bubble growth. For a rapidly varied liquid film, the confocal optical sensor is employed because the sensor is equipped with a data acquisition rate up to 30 kHz, and able to measure thickness ranging from several μm to 3 mm with nominal spatial resolution up to less than 1 μm. In the present study, the confocal optical sensor, fixed on a linear guide system (Igus, model DryLin), is incorporated with a controller (optoNCDT2431) which is also connected to a special Xenon light source. By detecting the reflections from the upper and the lower surfaces of the liquid film, the film thickness can be efficiently and accurately deduced. The detailed principle of the confocal optical sensor is accessible in [22].

A copper block with imbedded six cartridge heaters (CIR-30224 230 V 400 W) is employed as the heat source attached to the downward surface of the metallic test sections, which can provide up to 4 MW/m^2 heat flux to the liquid film. The power level of the cartridge heaters is regulated by a DC power transformer and the temperature profile of the copper block is monitored by K-type thermocouples. In order to eliminate condensation of vapor on the upper surface, an AC heater power supply is applied to preheat the air flow before it enters the test section.

2.2. Experimental method and procedures

For adiabatic tests, the water and air are supplied separately to the water-air inlet section at room temperature to form a stratified flow. For boiling tests, de-ionized water is firstly degassed about 30 min and then cooled down to the room temperature. Afterwards, water is circulated by the pump to the test section and compressed air is also provided to the channel after filtering and pre-heating. When the flow becomes stable at the given liquid and air flow rates and heat flux, the confocal optical sensor is operated to measure the dynamic liquid film thickness profiles along