AN EXPERIMENTAL STUDY ON THE DYNAMICS OF A LIQUID FILM UNDER SHEARING FORCE AND THERMAL INFLUENCE

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ABSTRACT

A profound knowledge of dynamics and instability of a liquid film is crucial for the thorough study on the physical mechanisms of boiling crisis (i.e., departure from nucleation boiling -- DNB, and dryout), which is important to the performance and safety of light water reactors. To address this, a series of tests were carried out at various water and air flow rates under atmospheric pressure and different heat fluxes. A confocal optical sensor system was employed to investigate the dynamics of a liquid film in a horizontal aluminum channel. The liquid film was sheared by co-flowing air from above and heated from below. We obtained the experimental data about the variation of thickness of the liquid film under different flow conditions and tried to analyze how it is affected by liquid/gas flow rates, shearing force and heat flux. We found that the shear force, evaporation and the generation of the bubbles enhanced the instability of the liquid film. We also found that the occurrence of the rupture was random and the critical thickness at the rupture increased with increasing heat flux. The spectrum analysis indicated that the effect of the shear force on the liquid film instability became weak when the liquid film is very thin, but the heat flux always enhanced the instability of the liquid film.

KEYWORDS
stratified flow, liquid film dynamics, instability, rupture, shear force

1. INTRODUCTION

Liquid film flow driven by a forced gas/vapor flow (stratified or annular flows) is frequently encountered in various engineering applications, from refrigerators to power plants. In such a two-phase flow system, the behavior of the liquid films on solid surfaces (so-called micro- and macro- layers in boiling) play an important role in determining the performance of the system [1]. The recent studies [2-3] indicates a “scales-separation phenomenon” which suggests that high heat flux and heat transfer of pool boiling are dominated by micro-hydrodynamics of the near-wall liquid film, and irrelevant to the external-scale hydrodynamics. This provides rationale for the boiling experiment performed on a thin liquid film [4] so as to facilitate the diagnosis of the film dynamics.

A good number of experimental and theoretical studies have been carried out to investigate the liquid film instability and rupture phenomena [5-8]. Oron et al. [9] provided perhaps the most comprehensive review of the multifaceted subject of thin film dynamics modeling. They presented a unified mathematical system to predict the long-scale evolution of thin liquid films, based on the long wave theory. The set of mathematical evolution equations has its root in the work of Burelbach et al. [10], taking into account the influential factors such as van der Waal forces, surface tension, gravity, thermo-capillary, mass loss and vapor recoil force. Craster and Matar [11] presented a comprehensive review of the work carried out on thin films flows, focusing attention on the studies undertaken after the review by Oron et al. [9]. Orell and Bankoff [12] performed experiments to investigate the formation of a dry spot in a non-boiling thin film of ethanol creeping on a horizontal surface, and found the downstream film thickness around dry spot is 450-660 μm in the heat flux range of 3-15 kW/m^2. Though some theoretical models and numerical simulations for boiling heat transfer were presented based on the concepts of near-wall liquid layers with the thickness estimated to range from several to hundred [13-18], little an experimental quantification of such thin liquid films and their dynamics is not straightforward, since 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 impede direct observation and measurement on thin liquid films, especially under high heat flux conditions. However, the related data is useful to analyze the liquid film dynamics and interfacial wave behaviors. The minimum thickness is of special interest since it is related to film rupture. For instance, the thinnest film may be torn off by high gas velocity.

The present study is to advance the developed experimentation and measurement techniques to measure dynamics of liquid film under forced flow condition (stratified flow) which is encountered in engineering applications. The previous hardware development and research findings are instrumental to the present work by using the similar setup (formation of a liquid layer) but adding the effects shear force induced by gas/vapor flow above the thin liquid layer. While using the same diagnostic systems as in the previous works [19-22], a new test rig is designed and developed to provide well-controlled flow conditions. The unique feature is still to measure the liquid film thickness evolution by the confocal optical sensor [19].The present study is to enrich the database of liquid film behavior in stratified flow.

2. EXPERIMENTAL SYSTEM AND METHOD

2.1. Experimental System

The experiments have been performed on an air-water test facility available in KTH. Original diagnostic system with confocal optical sensors [19] was developed to probe liquid film thickness and its evolution, and successfully employed to investigate the stability and rupture of a free liquid film under thermal influence [20], and the dynamics of a liquid film boiling on an open heater surface at both low heat flux [21] and high heat flux [22]. Two connection adaptors are delicately designed here, making water and air injected into the test section in parallel and generating stratified flow with minimum entrance effect. The schematic of the test facility is as shown in Fig. 1, which is mainly composed of water and supply systems, heating system, test section as well as measurement system. The test section is a rectangular channel made of aluminum (length × internal width × internal height: 155 *mm* × 8 *mm* × 12 *mm*) and the measure point locates at 110.2 *mm* away from the inlet of the channel, which insures that the measurements are corresponding to the fully developed equilibrium stratified flow. A copper block imbedded by six cartridge heaters (CIR-30224 230V 400W) is employed as the heat source. The confocal optical sensor is employed to obtain the variation of the liquid film thickness with time and track the evolution of the time-averaged thickness profile over a range of air and water flow rates.

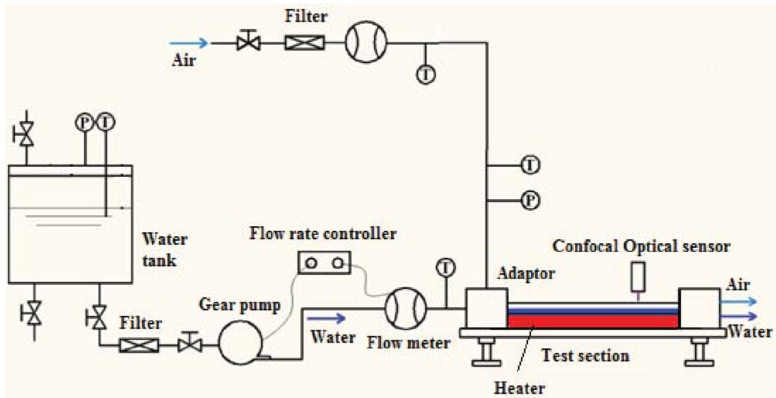
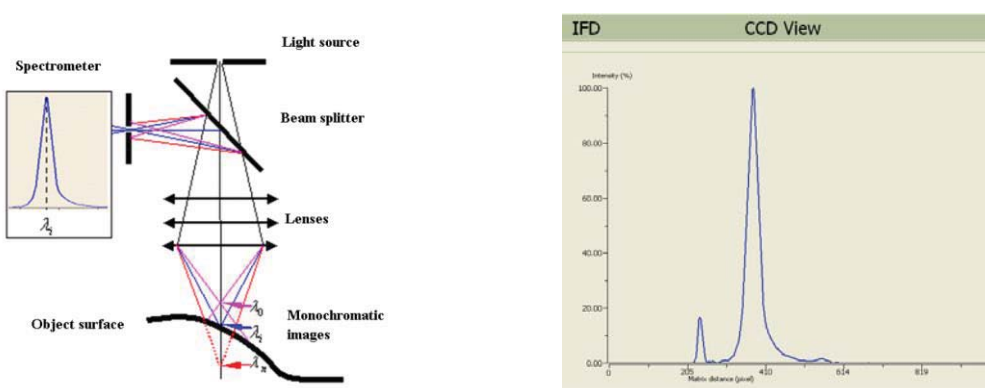


Figure 1. Schematic of test facility.

The reliability and feasibility of the confocal optical sensor for thickness measurement of a thin liquid film have been demonstrated [19] and the measuring principle of the confocal optical sensor is shown in Fig. 2. A beam of polychromatic light is dispersed to a series of monochromatic light (denoted by wavelengths from λ_0 to λ_n) through an optical system of multiple lenses. Consequently, the white light source is imaged by the objective lenses on continuous points along the optical axis in the measurement space. When a measured object is placed in the measurement space, a single of the monochromatic point images (with wavelength of λ_i) is focalized on the object interface. Due to the confocal configuration, only the light of wavelength λ_i is reflected through the objective lenses and directed towards the spectrometer with high efficiency, all other wavelengths will be out of focus. The spatial peak on the spectrometer indicates the position at which the measured object surface intercepts with the optical axis. When a transparent object is placed in the measuring space, the reflections from the upper and the lower surfaces of the object will be detected by the spectrometer as two peak signals and the thickness of the object is therefore deduced [19].



(a) Principle of confocal optical sensor.

(b) CCD view of confocal optical sensor for still liquid film

Figure 2. Measuring principle of confocal optical sensor system [19].

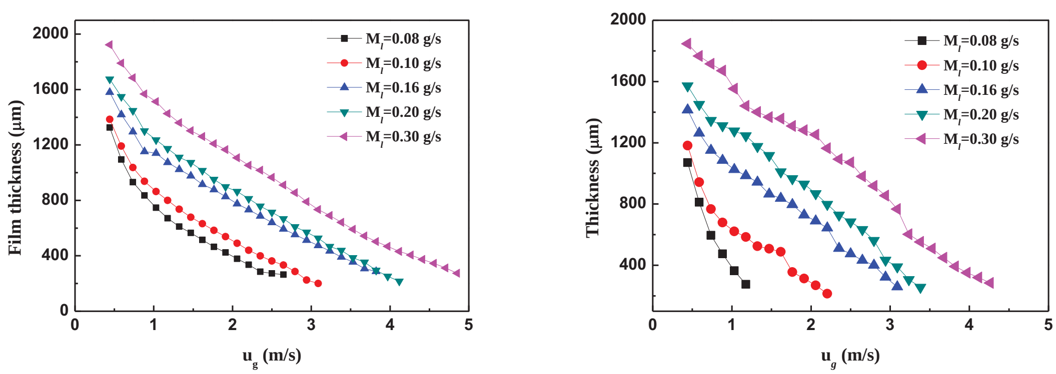
2.2. Data uncertainty

The water flow is measured by a Coriolis mass flowmeter with the uncertainty of 0.5%, and the air flow is measured and regulated by a thermal mass flowmeter with the function of flow control with the accuracy of 0.3%. The sensor IFS2431-3 selected in the present study has a maximum sampling rate of 30 kHz, measurement range of 3 *mm*, spatial resolution of 0.12 *μm*, and maximum tilt angle of ± 22˚. Inevitably, during the heating process, the generation of bubbles makes the liquid film unstable, which makes the data not constant. In particular, the bubble on or traveling through the measure point may cause the error data. In addition, the rupture of the liquid film occurs at random. In the present paper, we only concern the liquid film ruptured by the incoming gas at the measure point.

In the present study, the gas velocity ranges from 0.31 to 5.02 *m/s* and the liquid mass flow rate ranges from 0.08 g/s to 0.30 g/s, respectively. Heating and without heating experiments were both carried out. In order to prevent dramatic generation of bubbles, the heat flux was about 23 kW/m^2. All experiments were carried out under the atmospheric pressure. In each experiment, the measurement of liquid film thickness is carried out by sampling the data at 1000 Hz over a time period of 25 *s*. For the test running for investigation of the film rupture, the gas flow rate increases slowly until the rupture occurs at a given liquid flow rate and this process repeats five times for each flow condition.

3. RESULTS AND DISCUSSIONS

Variation of the time averaged film thickness with different gas and liquid velocities and heat flux are shown in Fig. 3. Obviously, the time averaged film thickness increases with the increase in liquid mass flow rate, but decreases with the increase in gas velocity. Due to the process of evaporation and generation of bubbles making the liquid film unstable, it appears that the film thickness decreases smoothly without heating, but shows obvious vibration when the heating is on. It is also worth noting that, especially when liquid mass flow rate is low, the time averaged thickness of liquid film firstly decreases sharply and then shows a linear dependence on gas velocity.

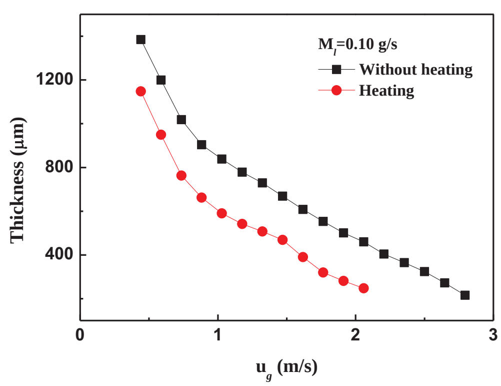


(a) without heating (b) with heating

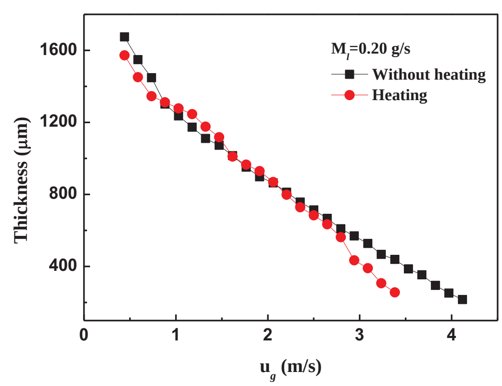
Figure 3. Variation of the liquid film thickness under different flow condition.

Typical comparisons of the time averaged film thickness under different conditions are shown in Fig. 4. It can be inferred from the figure that the evaporation affects the thinning process of the liquid film significantly when the mass flow rate is low (Fig. 4a). By increasing the liquid mass flow rate, the gap between two measured value between the heating and without heating decreases. In this circumstance, the time averaged film thickness under heating condition equals or even larger than that without heating (Figs. 4b and 4c). That is because the generation of bubble might cause the liquid film unstable and the growth of the bubbles makes the liquid among bubbles accumulate, resulting the local film thickness increases. When the thickness of the liquid film decreases to a specific value, the generation of bubbles ceases and the evaporation dominates the thinning process again.

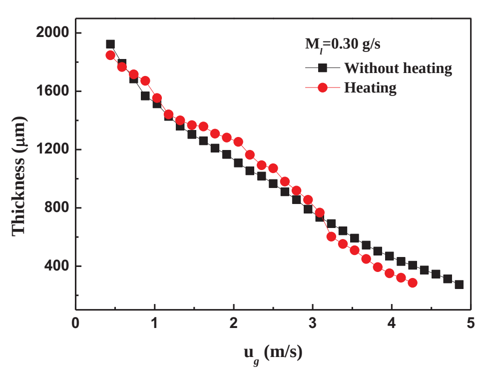
By increasing the gas velocity to a certain value, it was observed that a liquid film ruptures when it was thinning to a threshold value (called critical thickness). Analysis of the point when liquid film gets ruptured in vary tests is shown in Fig. 5. It can be seen from the figure that the range of critical film thickness increases with the increase in liquid mass flow rate. In addition, it seems that the critical film thickness shows weak dependence on the gas velocity without heating, but is affected by gas velocity under heating condition. Fig. 6 shows the average value of the critical liquid film thickness. The critical thickness of the liquid films performed in the tests was found to increase with increasing heat flux.



(a)

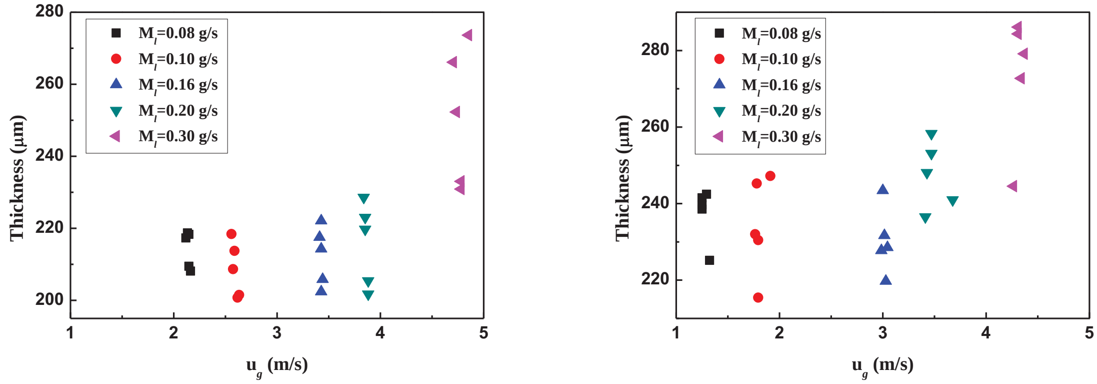


(b)



(c)

Figure 4. Typical comparison of the variation of time averaged film thickness.



(a) without heating (b) with heating

Figure 5. Critical film thickness under different flow conditions

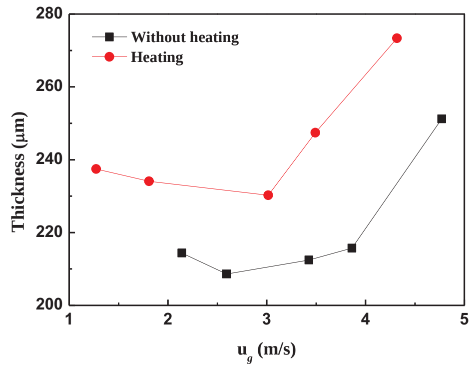
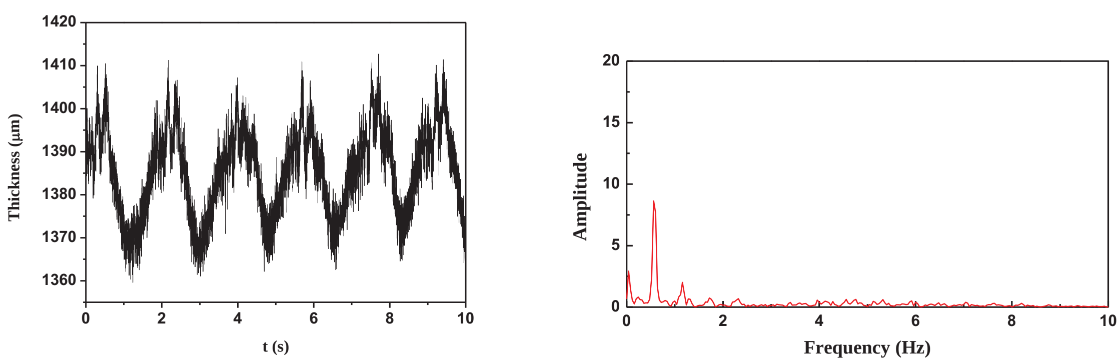


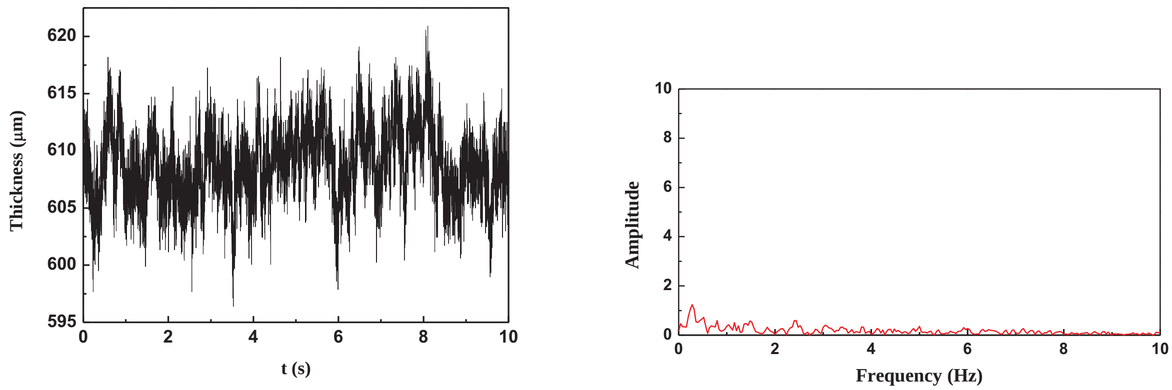
Figure 6. Averaged critical film thickness

Fig. 7 shows the liquid film thickness time trace and spectrum measured at liquid mass flow rate of M_l= 0.1 *g/s* under different gas velocity without heating. The figure indicates that when the gas velocity is low, the time averaged liquid film is relative thick and the spectrum has a strong dominant frequency. By increasing the gas velocity (thinning the liquid film), the spectrum has multiple components and is spread out. The dominate frequency gets weak and moves to the lower value.



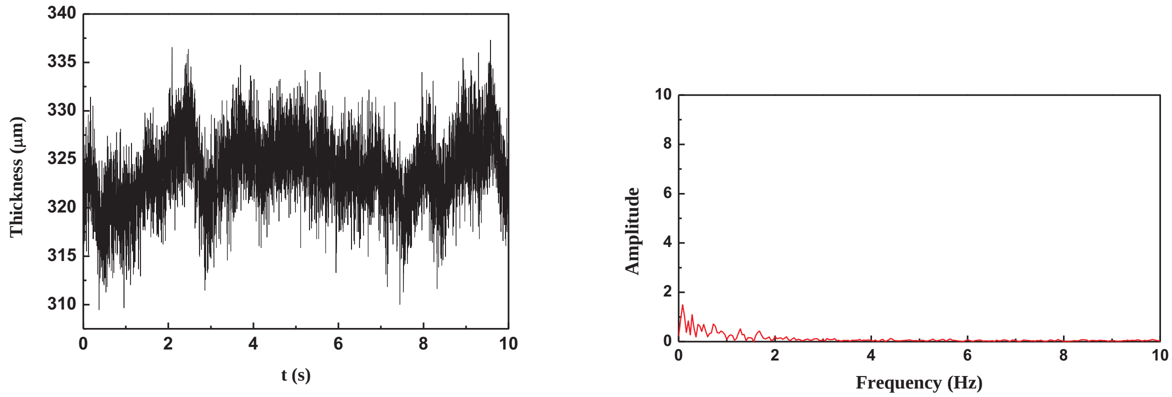
time trace spectrum

(a) u_g= 0.44 *m/s*



time trace spectrum

(b) u_g= 1.32 *m/s*

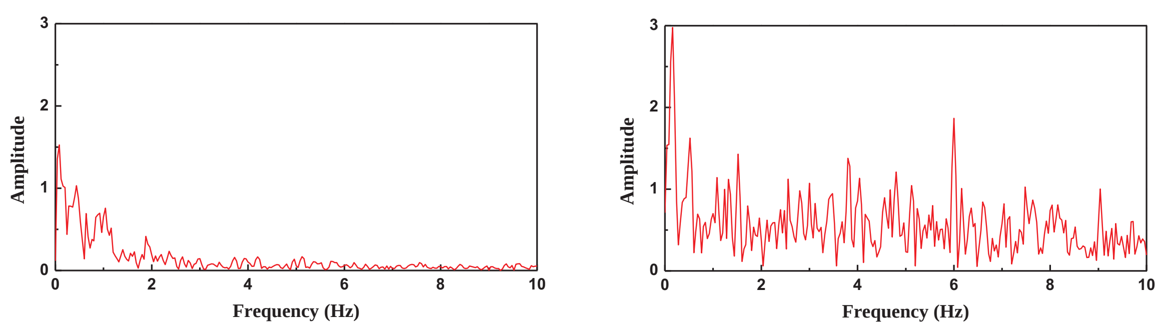


time trace spectrum

(c) u_g= 2.20 *m/s*

Figure 7. Liquid film thickness time trace and spectrum (M_l=0.1 *g/s*).

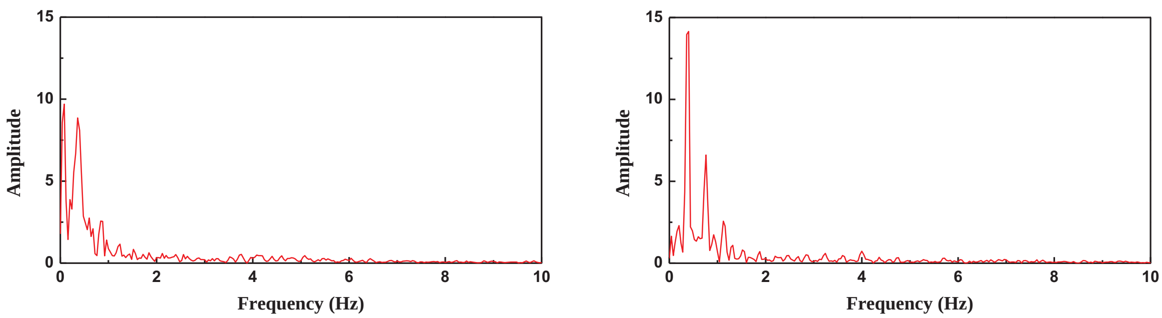
Fig. 8 shows effect of the liquid mass flow rate on the spectrum of the film thickness under the same gas velocity. It can be inferred from the figure that by increasing the mass flow rate, the spectrum has multiple components and the relative strengths of each individual frequency are similar, which indicates that the liquid film is more chaotic.



(a) M_l=0.10 g/s (b) M_l=0.20 g/s

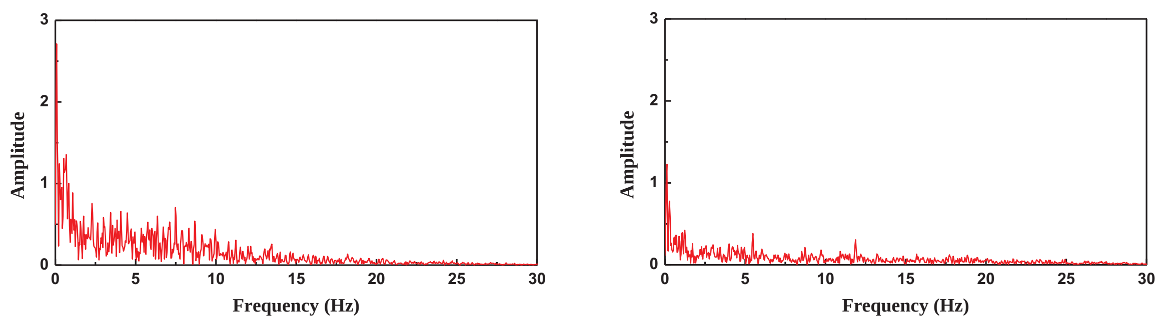
Figure 8. Spectrum of liquid film thickness under different liquid mass flow rate (u_g=2.20 *m/s*).

Fig. 9 shows the effect of the heat flux on spectrum both under initial film thickness and when reaching critical film thickness conditions. When the liquid film is relative thick (initial film thickness), two dominate frequencies are found on the spectrum and move to higher frequency with heating. When reaching the critical condition, heat flux enhances the chaotic of the liquid film.



Without heating With heating

(a) initial liquid film thickness



Without heating With heating

(b) Critical liquid film thickness

Figure 9. The effect of heat flux on spectrum of film thickness.

4. CONCLUSIONS

In summary, we investigated the dynamics of a liquid film under shearing force and thermal influence in a horizontal aluminum channel. According to our observations, the liquid film thickness firstly decreases sharply and then shows a linear dependence on gas velocity especially when the liquid mass flow rate is low. We also found the liquid film instability depended on the difference between the gas and liquid velocities which is related to shear force. In addition to the shear force, the evaporation and the generation of bubbles, which are affected by heat flux, had great effects on the film thickness variation and instability. The occurrence of the liquid film rupture was random, and the critical thickness at the rupture increased with increasing heat flux but showed weak dependence on the gas velocity when without heating. Namely, the heat flux enhanced the liquid film instability. Based on the spectrum analysis, relatively dominant frequencies were found when the gas velocity was low but the spectrum had multiple components and spread out by increasing the gas velocity.

ACKNOWLEDGMENTS

This study is supported by the NORTHNET program. The authors would like to thank our sponsor, not only for the support but also for their suggestion, feedback and insight into the project. The assistance of Louis Manickam with setup of observation system (high-speed camera) is greatly appreciated. The authors also wish to acknowledge Aram Karbojian, Lars-Erik Storm, Per Sköld and Mikael Johansson at the NPS Laboratory of KTH for their technical support on the experimental setup.

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