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Thermal imaging study on the surface wave of heated falling liquid films

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ABSTRACT

By using thermal imaging technique and film thickness metering system, the surface wave and film thickness of the heated falling liquid film were experimentally investigated. Temperature variations of the heated film induce surface tension gradient and so-caused Marangoni flow that attempts to avoid the temperature variations. There are three kinds of Marangoni flow appearing in the heated falling liquid film. It is found that the lateral Marangoni flow (MF I) and the streamwise Marangoni flow (MF II) make the heated film thick, while the Marangoni flow in the surface wave (MF III) reinforces the wave and makes the heated film thin. The intensity of Marangoni flow is determined by the flow rate and the heating conditions. MF I and MF II are both enhanced with the increasing liquid flow rate. Moreover, MF III is prominent under moderate flow rates and is gradually weakened at high flow rates. The distance over which MF III starts, increases with a rise in flow rate, but is independent of the heating condition.

1. Introduction

The falling liquid film over a solid is one of the most common patterns encountered in the industrial equipments such as vertical condensers, film evaporators and absorption towers. In order to design these industrial equipments reliably, the rates of heat and mass transfer must be accurately predicted for the films. Since the characteristics of falling liquid films (such as film thickness, surface waves, temperature distribution and film instabilities) are closely relative to the heat and mass transfer, there have been a number of attempts to investigate the falling liquid film via both practical and theoretical approaches in the past years [1–3]. Nusselt [4] performed the fundamental work on the laminar falling liquid film. He established a series of equations for the velocity profiles, heat transfer and the film's thickness. Portalski [5] discussed the applicability of the previous theories to the experiments and reviewed the measurement of isothermal film's thickness. Nowadays, with the significant development of detection techniques, new apparatus such as thermal camera, PIV, High speed camera, etc., are gradually utilized in the research, thus the flow characteristics of the film and their influences on the transfer processes could be studied in detail [1,3,6–8]. Besides the experimental approaches, numerical method based on the Computed Fluid Dynamic is also applied to explore the construction and nonlinear instability of the film [9,10].

Since thickness is one of the most important properties of a falling liquid film, film thickness was measured with several methods, such as the electrical conduction, capacitance, needle and luminescence techniques. The selection of an appropriate measurement is decided by the task of the study and the accessibility of the equipment [11]. The researches of film thickness reveal that surface waves inevitably occur even in a viscous liquid film with very low flow rate, making the film thinner and enhancing the heat mass transfer [12,13]. Due to the important applications in industry and laboratory, the liquid film flowing over a heated plate is paid special attention. Schagen and Modigell [13] successfully obtained the local film thickness and temperature distribution in wavy liquid films with a laser-induced luminescence technique. In the non-isothermal liquid film, Marangoni flow can be induced by surface tension gradients (due to the variations of concentration or temperature), and can drive the liquid particles toward the direction of the higher surface tension side. In general, temperature variations in the surface of the heated film affirmatively leads to Marangoni flow (thermocapillary caused by surface tension gradient) that deforms the film surface [14]. Zaitsev [15,16] has performed experimental work on the thermocapillary deformations of heated ethanol–water film and water film by measuring the local film thickness with a double-fiber option probe. Their measurement was based on the dependence of the reflected light's intensity on the distance between the probe and the reflecting surface. Utaka and Nishikawa measured condensate film thickness for solutal Marangoni condensation with laser extinction method. They found good agreement between the film thickness data and

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condensate behaviors observed by a high-speeded camera [17]. It is worthy to note that the measurement of heated film thickness is better to be non-invasive and sensitive, since the Marangoni flow is easily affected by the disturbing on the surface of film. In the present work, the capacitance method is used to measure the thickness of liquid film, since it is non-invasive, highly sensitive and of easy operation [18].

In the heated films, the coupled thermocapillary and surface wave instabilities could create surface deformations and influence the transfer process [19,20]. Hereby, a good understanding of temperature distribution of the film makes clear the reciprocities between the thermocapillary and the surface waves, and helps the designing and operating of the film devices. Infrared thermal imaging technique can provide precise non-contact temperature measurement and is very useful in the study of heated falling liquid film [6,7,21]. By using a thermal imaging technique, the surface temperature distributions and their effects on the liquid films flowing over a vertical heated plate could be successfully obtained. The film thickness was also measured by capacitance method to reveal the influences of Marangoni flow on the film thickness and surface waves, simultaneously.

2. Experimental setup

2.1. Test section

The schematic diagram of experimental system is illustrated in Fig. 1. The test section consists of the liquid distributor (its exit gap is 85 mm wide), a carefully polished stainless steel plate installed vertically ($300 \times 300 \times 6$ mm in length, width and thickness), water heater ($300 \times 300 \times 50$ mm in length, width and depth) on the back side. Two probes (6 mm in diameter) connecting to the film thickness meter are located in the upper and lower part of the plate, respectively. The surface temperature of the film and liquid distributions on the plate could be accurately recorded by a highly sensitive infrared camera system – ThermaCAM™ SC3000, manufactured by FLIR System Company, USA. The accuracy of this system is within ±0.1 °C and its instantaneous field of view (IFOV) is 1.1 mrad. The thermal camera and film thickness meter were both connected to a PC machine with the data auto-saved every 2 s and 1 ms, respectively. The whole test section was placed in a closed transparent shell to avoid the disturbing of the air around the film.

In this experiment, distilled water and glycerol–water solutions (8–50 wt%) were used as working liquids. The physical characteristics of the working fluid and the fundamental parameters of the experiments are given in Table 1.

2.2. Measuring technique

In the experiments, the metal probe of the film thickness meter, the surface of the liquid film, and the air between the probe and film make up of a capacitor. As a liquid film flowing between the probe and the plate, the voltage of the capacitor varies accordingly. The thickness of the liquid film can therefore, be obtained from the relationships between the film thickness and the voltage of the capacitor.

2.2.1. Theory of capacitance method

In general, a capacitor consists of two conductive plates, separated by a dielectric medium. As the distance between the two plates or the medium changes, the voltage of the capacitor varies accordingly. The sketch of the circuitry for the capacitance measurement is depicted in Fig. 2, where C_s and C_T denote the standard capacitance and parallel plate capacitance, respectively. h represents the space between the probe and the object. V_s is the AC signal source voltage and V the output voltage of amplifier. During the measurement, the object is connected with the Earth. According to the theory of the feedback operational amplifier, the relationship between V_s and V is expressed as

$$V = -\frac{C_S}{C_T} V_S \quad (1)$$

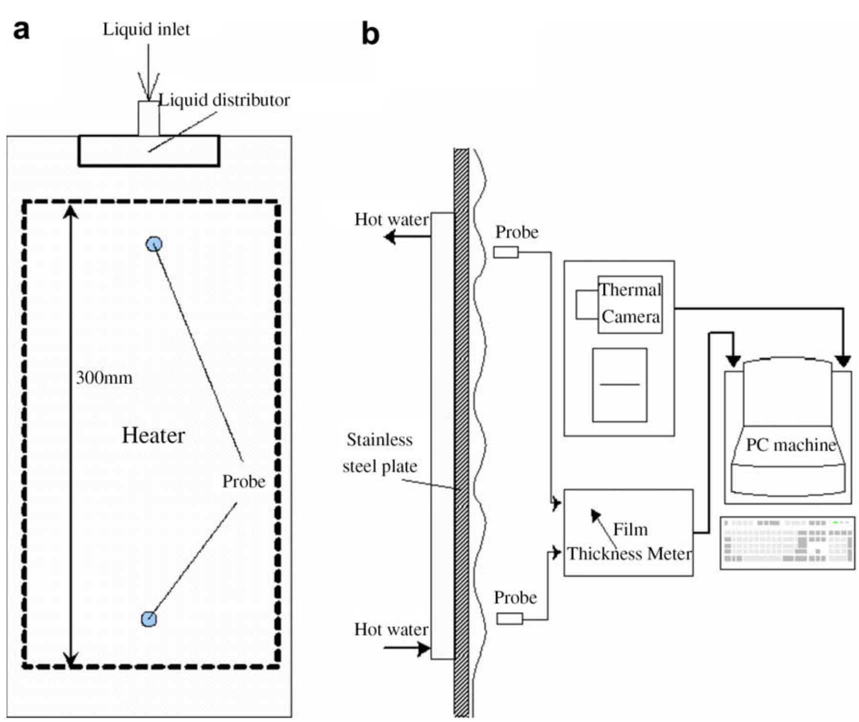

Fig. 1. Sketch of the experimental system (a) front view (b) cross section view.