

Experimental Study on Interfacial Film Dynamics of Oscillating Multiphase Micro Flows

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Abstract Research on interfacial film dynamics, fluid flows, heat and mass transfer in mini/microchannels is a rapidly emerging area in studying micro fuel cells, DNA separation and analysis, valveless micro pumps, micro heat pipes, and in micro-fluidic research. This paper is to report some fundamental aspects of interfacial film dynamics of plug/slug flows in a capillary tube in order to predict and optimize the behavior of multiphase flows in micro spaces. A novel optical technique has been developed to measure the liquid film thickness of a plug like bubble in a capillary tube utilizing spatial fringe scattering method. The scattered fringes were measured by a CCD camera and the calculated spatial frequencies were used to determine the interfacial film thickness between the plug and the channel wall. The uncertainty of the measurements was less than $\pm 0.2\mu\text{m}$ ($\pm 2\%$) for a confidence level of 95% in the experiments. Utilizing the newly developed measurement technique, the interfacial film dynamics of oscillating plug/slug flows in a capillary channel was investigated. It is found that the pre-wetted interfacial film thickness could not be zero when the bubble is under static conditions. Also stepwise film thickness variations have been found when the oscillating frequency changes. Furthermore, when the oscillating frequency reaches to 15Hz, periodical film thickness has been found. Further increasing the oscillating frequency (such as to 40Hz) will result in wave-like interfacial film thickness variations. It also demonstrated that the oscillating frequencies of the micro plug/slug flows do have significant impact on the interfacial film thickness.

1. Introduction

Recent progresses in lab-on-a-chip and μTAS , microsurgery, micro fuel cells, electrokinetic micro pumps micro heat pipes and micro fluidic research have yielded a rapidly emerging area in manipulating and control of multiphase flows and heat transfer in mini/microchannels. Examples include a high efficient gas-liquid-solid micro fluidics hydrogenation reactor (Kobayashi et al. 2004), a promising technique utilizing air-bubble method of catheter locking with anticoagulant at the catheter tip and bactericidal properties at the catheter hub for hemodialysis access (Moore and Twardowski, 2003), prevention of gas embolism damage in surgery caused by intravascular air bubbles carried in the bloodstream (Branger and Eckmann 1999, Ayyaswamy 2004), manipulating microbubbles by ultrasonic waves (Yamakoshi 2001), cooling of electronics devices using mini/micro heat pipes (Cotter, 1984, Groll et al., 1998). To accelerate multiphase catalytic reactions, some treatment producing high interfacial area between the two or three reacting phases is needed. The manipulation of interfacial liquid film thickness between the catalyst surface and reacting gas can further optimize the process. Therefore, it is important to understand the physics of transport processes in a microchannel multiphase flow. A very classical and practical problem is the knowledge of the amount of liquid remaining on the wall of the tube, namely $h(V)$. This problem has been extensively studied in the limit of low velocities of deposition, in particular since Taylor's and Bretherton's first experiments (1961). After a brief summary of these regimes, we shall present

new data obtained at high velocity with liquids of low viscosity, which allows us to stress the influence of inertia on the film thickness. It has been found that the interfacial film dynamics play important role that affects the plug/slug flow, drag force and heat/mass transfer in mini/microchannels. The surface energy (Surface Wetting Capability) of the wall may have great impact on the interfacial film dynamics when a bubble plug/slug in a liquid flowing in a mini/microchannel. This indicates that the friction of multiphase flows may strongly depend on the wall property in a mini/microchannel. Modeling multiphase fluid flow at the micro-scale with the assumption of simple disjoining pressure and liquid surface tension may not be accurate. It will depend on the interactions between the fluid, gas/vapor, and the surface properties of the wall. Furthermore, due to the complexities of micro scale thermal capillary effects and the aspect ratio of the mini/micro channel, the relationship between the interfacial liquid film thickness, velocity, friction, plug/slug shape, temperature, and properties is not well understood.

Understanding the mechanisms behind the formation and dynamics characteristics of the interfacial film between plugs/slugs and mini/microchannels are important in optimizing aforementioned processes and applications. The physical behavior of multiphase flows in mini/microchannels is complex because it involves interfacial transport phenomena coupled with the dynamics of thin liquid, the disjoining pressure of the phases, stability and phase change at such an interface in microscale fluids. A particularly interesting phenomenon associated with multiphase flows in mini/microchannels is the interfacial film dynamics caused by the liquid surface tension, the surface energy of the wall, the flow and plug/slug velocities and the gas property. The crucial progress is that the newly developed optical diagnostic technique by Wang and Qiu (2005) which provides a useful tool to determine the interfacial film thickness and its variations with cylindrical capillary micro pipes. It was further extended to measure the interfacial film thickness for Immiscible Liquid-Liquid Slug/Droplet Flows (Qiu *et al.* 2005). In this paper, a novel optical diagnostic technique [10, 11] has been used to probe the liquid film thickness in micro capillary oscillating two-phase flows. The spatial frequencies from the multi-scattering measured by CCD camera are used to determine the film thickness. The very fine parallel fringes are projected onto the liquid/gas-bubble interface. The scattered fringe pattern can be imaged at a proper orientation angle where the spatial frequency of the fringe pattern can be measured. To determine the spatial frequency variations during the plug/slug pulsating, a highly accurate signal processing technique (Qiu *et al.* 1991) utilizing a modified fast Fourier transform algorithm was used. Through geometrical optics approach, the curvature of the cross-section of a plug can be derived from the spatial frequency of the scattering pattern on the screen. By assuming the plug is rotationally symmetric about its centerline, the film thickness of the plug is obtained. To demonstrate the capability of the newly developed technique, a validation experiment was conducted with water/air and water-honey-mixture/air plug flows. The effect of oscillating frequency on the interfacial film thickness has been measured and analyzed. It demonstrated that the oscillating frequencies of the micro plug/slug flows do have significant impact on the interfacial film thickness. In this paper, the experimental and analytical results, as well as the measurement technique will be presented in detail.

2. The Measurement Technique

The layout of a plug passing through a micro capillary tube is described in Figure 1, where the gas-liquid interfacial film thickness can be assumed to be axis symmetric in most cases especially when the tube diameter is small. If an incident light is perpendicularly projected on to the capillary tube, the ray path passing the cross-sectional area of the plug and liquid film is shown in Figure 2.

According to Wang and Qiu (2005), the film thickness, h , can be derived as:

$$h = R - R \sqrt{c^2 \sin^2 \theta + \frac{1}{\left(\frac{1}{c \cos \theta} \frac{f_0}{f} + \frac{1}{\sqrt{1-c^2 \sin^2 \theta}} - \frac{1}{c \cos \theta}\right)^2}} \quad (1)$$

where R is the internal radius of the capillary tube, θ is the incident angle on the glass/liquid interface, c is the refractive index ratio between the glass and liquid, f and f_0 are the spatial frequencies of the received fringes in the receiving angle β direction for non-zero liquid film thickness and zero film thickness, respectively.

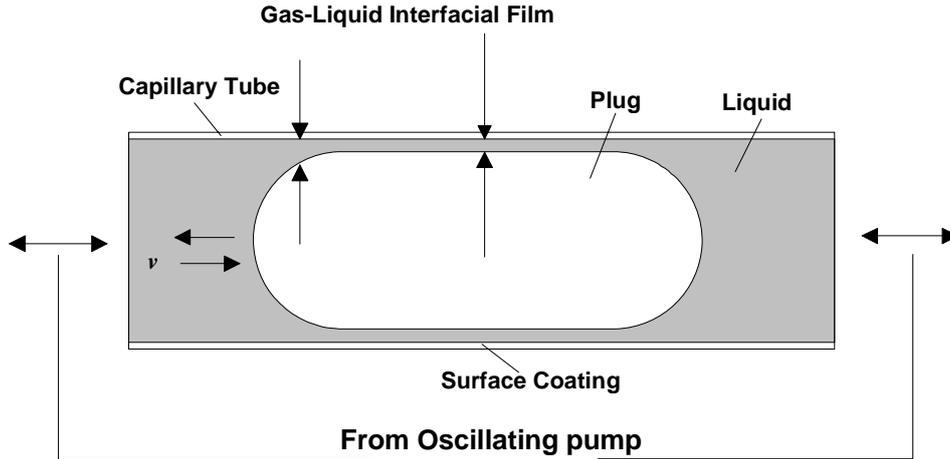


Figure 1 Schematic of Oscillating Plug/Slug Micro Flow Experiments

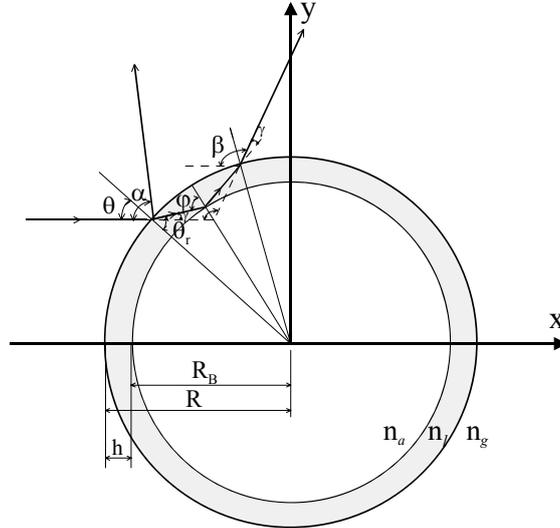


Figure 2 Schematics of geometrical optical approach of scattering rays from a gas plug

Considering the ray path for a given β , following relationship can be obtained:

$$h = R \left[\left(1 + \frac{\sin\left(\frac{\beta}{2} - \theta\right) \sqrt{1 - c^2 \sin^2 \theta}}{c \sin \theta} \right) - \sqrt{1 + \left(\frac{\sin\left(\frac{\beta}{2} - \theta\right) \sqrt{1 - c^2 \sin^2 \theta}}{c \sin \theta} \right)^2} \right] \quad (2)$$

Therefore, the interfacial film thickness h can be numerically determined by solving Equations

(1) and (2) if the spatial frequency ratio f_0/f can be measured. The spatial frequency can be measured accurately utilizing FFT and Five-Point Interpolation method.

3. Experimental Setup

The test channel is built with a borosilicate capillary tube which is horizontally immersed 10 mm under the top of a polymethyl methacrylate rectangular tank. The schematic diagram of experimental setup is shown in Figure 3.

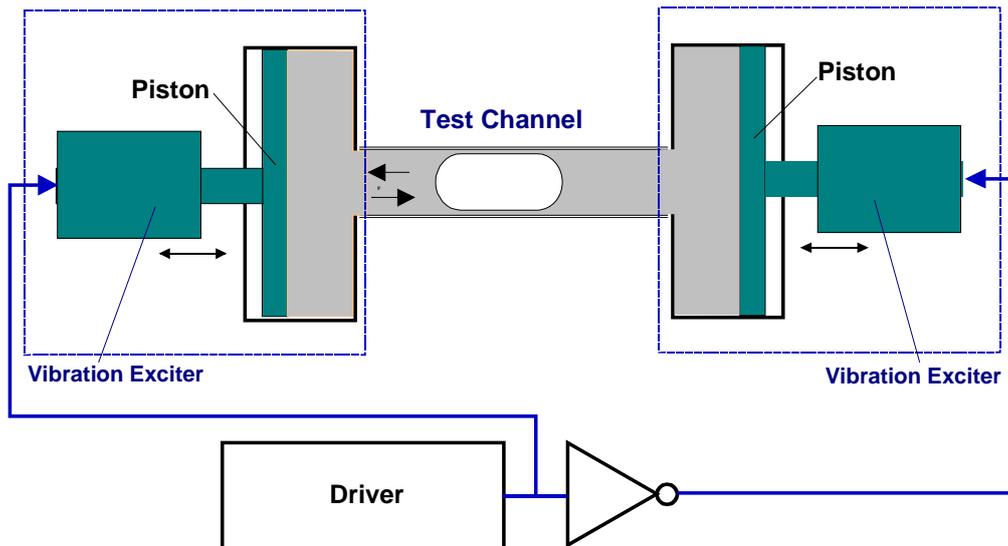


Figure 3 Schematic diagram for measurements of the liquid film thickness of a plug

The capillary tube is 100 mm long and with 750 μm inner diameter and 1500 μm outer diameter (ID=750 μm , OD=1500 μm). In order to reduce the effects of light reflection caused by the surface of the glass tube, the tank is filled with glycerol ($\text{C}_3\text{H}_8\text{O}_3$) that is one kind of clear viscous liquid with refractive index between 1.470 to 1.475 (20°C, 589 nm), which can well match the refractive index of 1.473 of the special borosilicate glass. Two reciprocating pistons are used to push and pull the channel flow in oscillatory directions. The pistons are driven by a vibration exciter (Type 4809, Brüel & Kjær) which can deliver a force rating 45N and frequency range up to 20 kHz. By changing the amplitude of the input sine wave, the amplitude of the displacement oscillation can be adjusted. The static and dynamic displacement of the plug bubble is measured. To measure the interfacial film thickness between the air plug and the glass wall, a uniphase mode 1135P, 15mW He-Ne laser ($\lambda=632.8$ nm), a beam splitter, and a lens with 200 mm focus were used for producing interference fringes. The distance between the two parallel split beams is about 50 mm. The total reflected fringes are measured by a high speed camera (Redlake color HG-100K) which is coupled with a Nikon L37c 52 mm optical lens and a 100 mm receiving lens. According to previous analysis, to receive the total reflection rays, the image system (includes the high speed camera and the receiving leans) is adjusted to collect the reflected fringes which within the angle of 90~120° from incident light direction. The measurement technique was validated with air plug in water and air plug in 70% water 30% honey mixture. In the validation experiments, the air plug is about several millimeters long (see Figure 4) and has a moving velocity less than 300 mm/s. The incident fringes pattern measured by CCD camera and the spatial frequency is calculated by using FFT and five point fitting method. The calibration curves are shown in Figure 5 where the interfacial film thickness versus the measured spatial frequency of the scattering fringe patterns is demonstrated. It

should be noted that for a micro plug bubble in a micro channel, the film thickness interested is from sub-microns to several microns, therefore, from Figure 5, we can conclude that the film thickness is almost linearly proportional to the measured relative spatial frequency f_0/f .

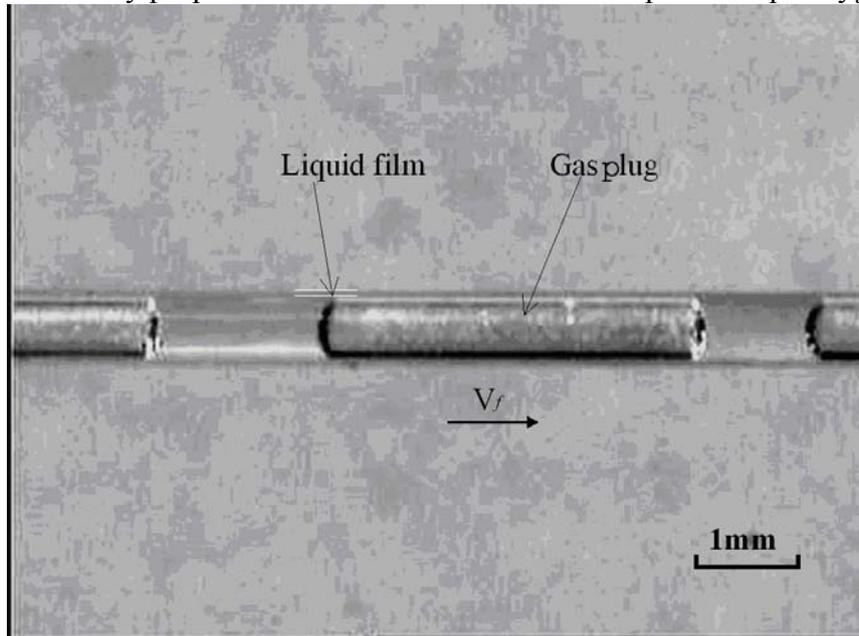


Figure 4 The image of water/gas-plug flow within a capillary glass tube

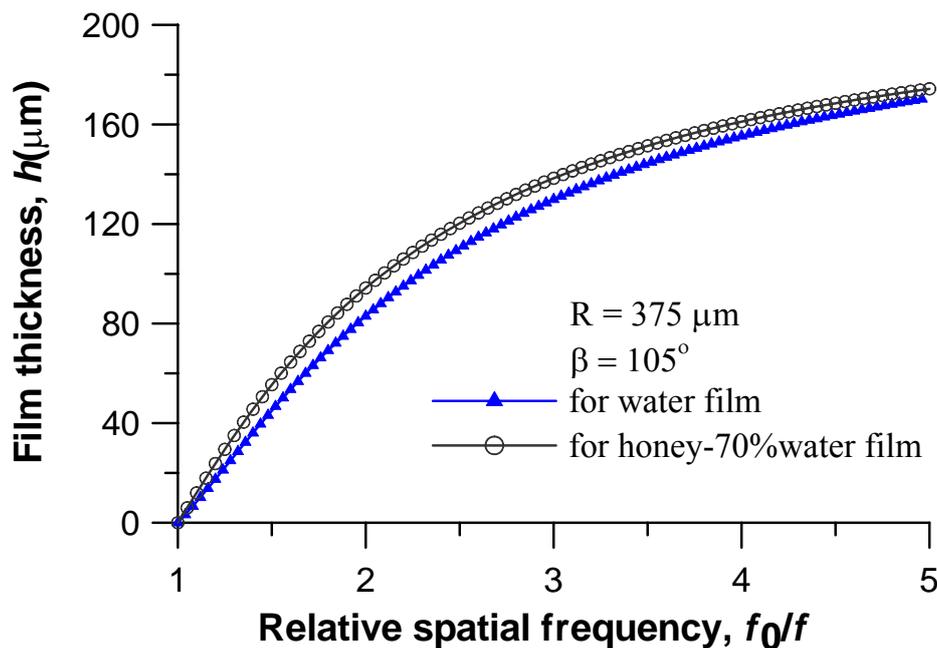


Figure 5 The relationship between the film thickness h and the measured frequency ratio f_0/f

The plug oscillations and velocities were measured using the image processing of the recorded plug position images. Figure 6 demonstrates an air plug (12 mm long) in water measured by a high speed camera (Redlake Color HG-100K). The oscillating frequency is 4Hz and the amplitude of the displacement is 4.5mm. The measurement cross-section of the laser is located at the dash line as shown in Figure 6. Therefore, during the plug oscillating, because the amplitude of the displacement is set smaller than the half length of the plug, the measurement cross-sectional position do not go beyond the plug range and even it can not reach to the front/end curvatures of the

plug. As a result, the measured film thickness mainly represents the interfacial film thickness at the center part of the plug during the oscillating process.

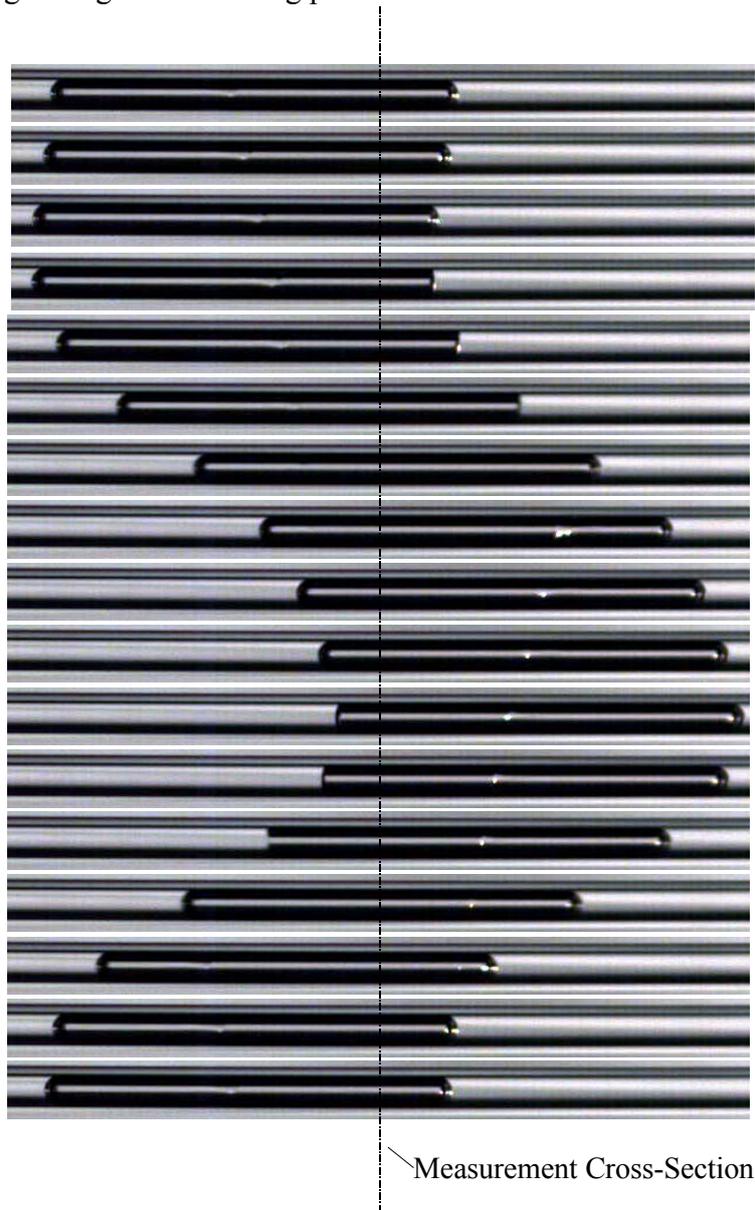


Figure 6 Images of oscillating bubble plug and measurement cross-sectional position

4. Results and Discussion

The measured interfacial film thickness varies with time and frequency is shown in Figure 7 to Figure 14. Figure 7 shows the measured film thickness when the plug bubble is in the state of rest (without motion). The measured film thickness is about $2.0\mu\text{m}$ and it is almost constant. When the oscillating frequency of plug increases to 1Hz (see Figure 8), the interfacial film thickness also increases slightly to $2.2\mu\text{m}$. However, no periodical fluctuation of film thickness varying with time can be observed. The interfacial film thickness increased significantly when the oscillating frequency reached 4.0Hz as shown in Figure 9. The film thickness changed to about $4.2\mu\text{m}$ and there are also some high frequency wave like variations in the film thickness can be observed. Because for 4.0Hz oscillating frequency, the half cycle is about 125ms and the period of the high frequency fluctuations is about 30ms, several the wave like variations in the film thickness can be assumed when the plug moving towards to one direction.

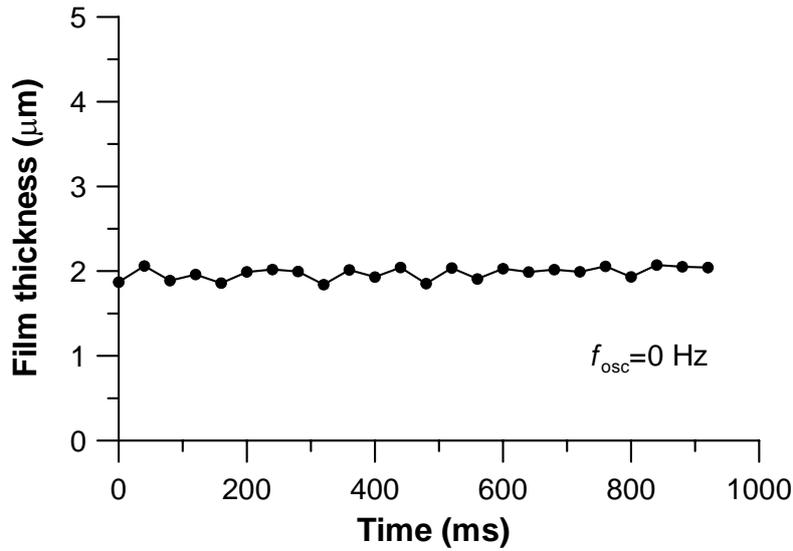


Figure 7 Measured interfacial film thickness under 0Hz oscillating frequency

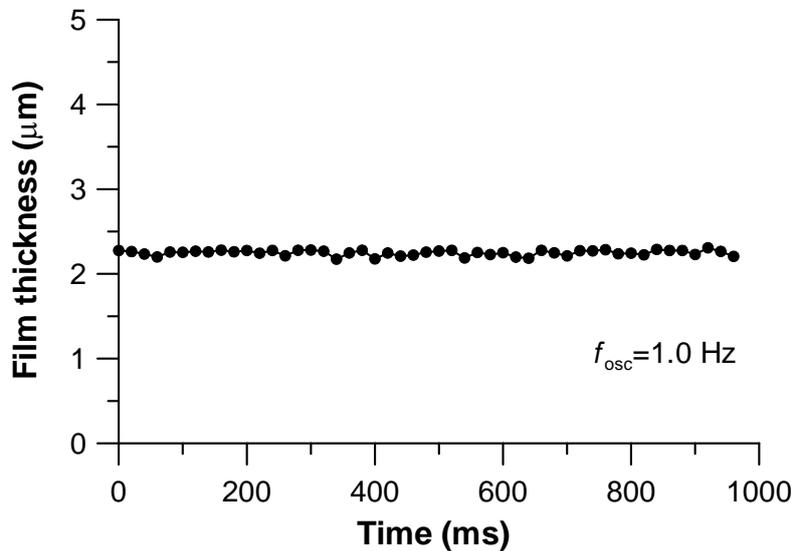


Figure 8 Measured interfacial film thickness under 1.0Hz oscillating frequency

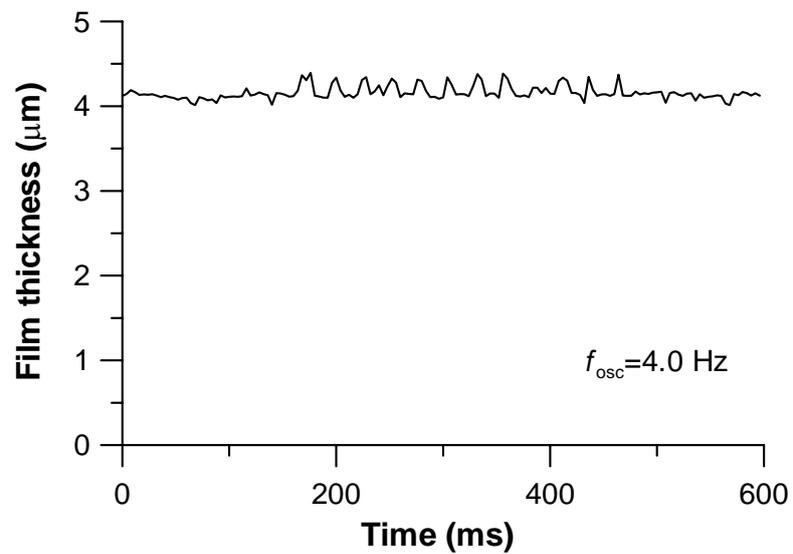


Figure 9 Measured interfacial film thickness under 4.0Hz oscillating frequency

Further increasing the oscillating frequency to 8.0Hz only slightly increases the interfacial film thickness to 4.3 μm , no significantly synchronized wave like film thickness can be observed as shown in Figure 10.

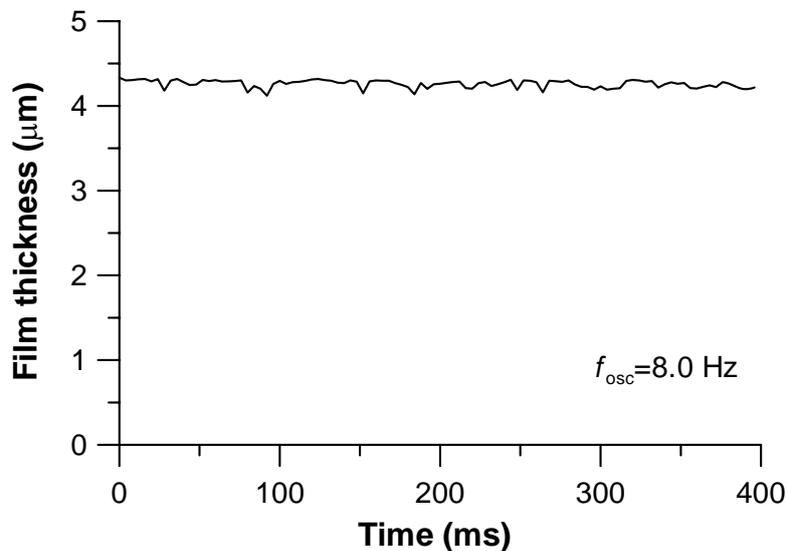


Figure 10 Measured interfacial film thickness under 8.0Hz oscillating frequency

According to Aussillous and Quéré (2000), the interfacial film thickness can be given as

$$h/r = 1.34C_a^{2/3} / (1 + 1.34 * 2.5C_a^{2/3}) \quad (3)$$

where C_a is the so called *capillary number* which is proportional to the plug velocity, r is the radius of the capillary tube and h is the film thickness. In fact, Eq. (3) was derived from $h/r \sim C_a^{2/3}$ which was originally from Taylor (1961) and Bretherton (1961). Therefore, from Figure 7 to Figure 10 it is found that the change of interfacial film thickness follows the tendency of Eq. (3), i.e. the higher the plug velocity, the thicker the interfacial film thickness. However, two differentiae have been found here. The first one is that according to Eq. (3), when the plug velocity is zero, the interfacial film thickness must be zero. However, as shown in Figure 7 the interfacial film thickness is about 2.0 μm . This static interfacial film thickness maybe explained by the intermolecular force (disjoining pressure) which was not considered by Eq. (3). Therefore, at the static state condition, the interfacial film thickness should depend on the surface energy (wetting ability) of the tube material and the intermolecular force at the liquid-air interface. The second finding is that the film thickness is not change continuously within very low plug velocity (C_a very small). As it can be seen in Figure 8 and Figure 9, the film thickness jumps from 2.2 μm to 4.2 μm with an oscillating frequency change from 1.0 to 4.0 Hz. However, the film thickness only changes from 4.2 μm to 4.3 μm when the frequency changes from 4.0 to 8.0Hz. As a result, a stepwise change in film thickness has been observed.

Furthermore, because the velocity of the plug bubble oscillating from $-V_m$ to V_m , where V_m is the amplitude of the plug bubble velocity, the film thickness should also oscillate from zero to its maximum value. However, no this kind periodical variation can be observed.

A synchronized periodical variation of liquid film thickness can be, however, found when the oscillating frequency becomes 15Hz as shown in Figure 11. The amplitude of the interfacial film thickness is 0.2 μm and the mean thickness is about 4.6 μm .

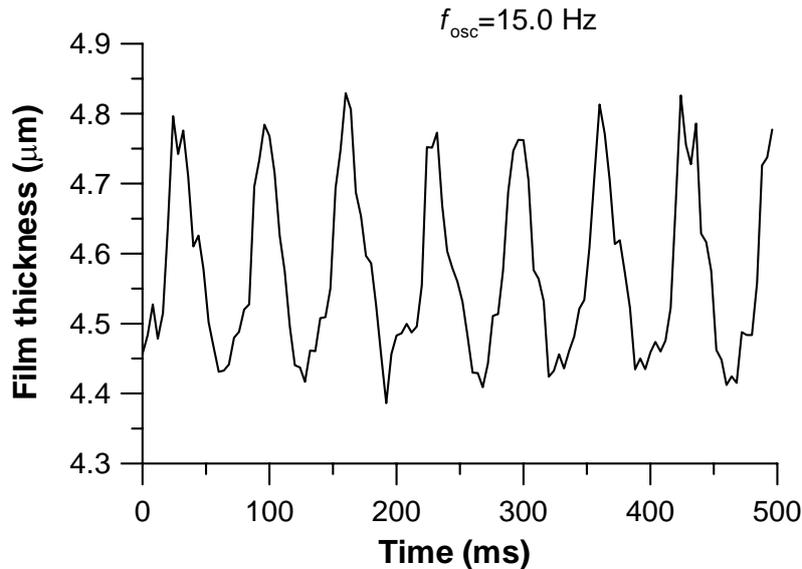


Figure 11 Measured interfacial film thickness under 15Hz oscillating frequency

Increasing the oscillating frequency to 20.0Hz will result in the maximum amplitude in the oscillating film thickness as indicated in Figure 12. The base film thickness is about 4.0 μm and the peak film thickness is about 7.7μm. It seems that the film thickness reaches its resonating condition and the peak thickness is doubled.

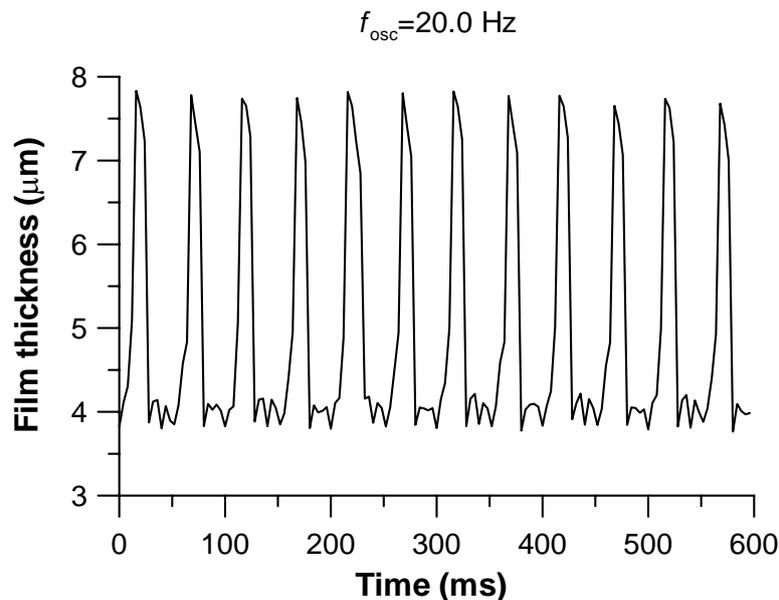


Figure 12 Measured interfacial film thickness under 20Hz oscillating frequency

Applying FFT analysis on Figure 12, we can find a strong harmonic power at the position of 40 Hz. This demonstrates a wave-like interfacial film thickness has been formed. This phenomenon is very important to pulsating micro heat pipe design. Further increasing the oscillating frequency to 30 Hz gives a similar the wave-like film thickness as demonstrated in Figure 13. The second harmonic power becomes stronger under this frequency although the amplitude of the interfacial film oscillating becomes smaller. It is interesting to observe that the second order harmonic wave-like film thickness disappeared when the exciting frequency reached 40 Hz (see Figure 14). Instead, a third order wave-like harmonics (120Hz) becomes visible as shown in Figure 15.

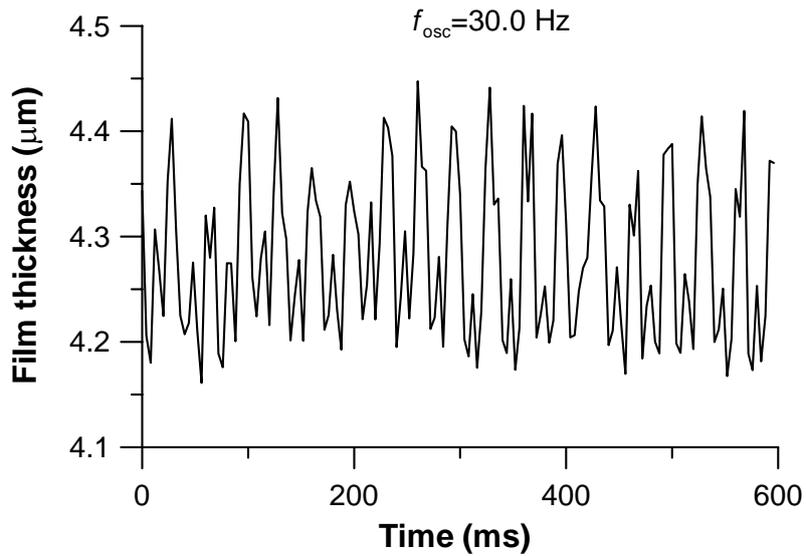


Figure 13 Measured interfacial film thickness under 30Hz oscillating frequency

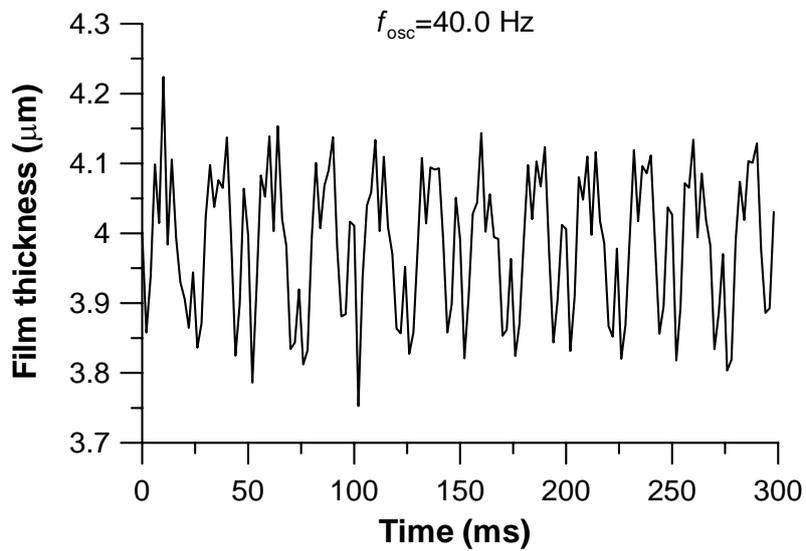


Figure 14 Measured interfacial film thickness under 40Hz oscillating frequency

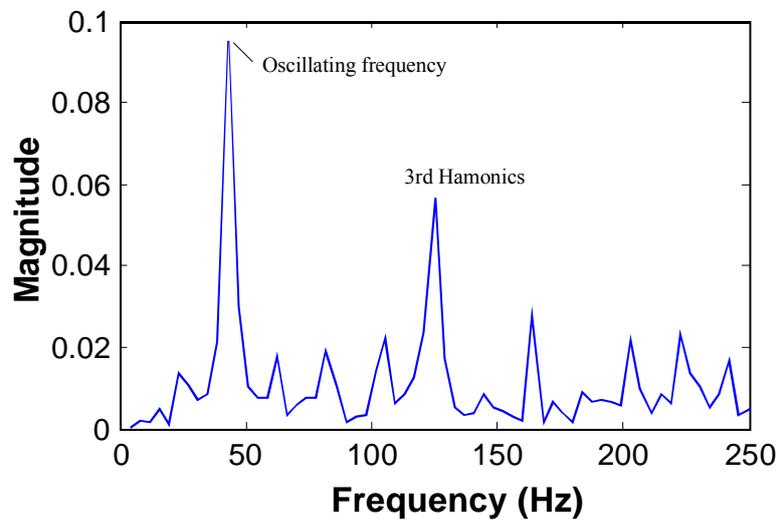


Figure 15 Frequency Spectrum of the interfacial film thickness for 40Hz exciting frequency

The relationship between the mean interfacial film thickness and the oscillating frequency is summarized in Figure 16. It concludes that when the oscillating frequency is small, the mean interfacial film thickness is also small. With increasing the oscillating frequency, the interfacial film thickness increases drastically. It becomes constant after the oscillating frequency above 40Hz.

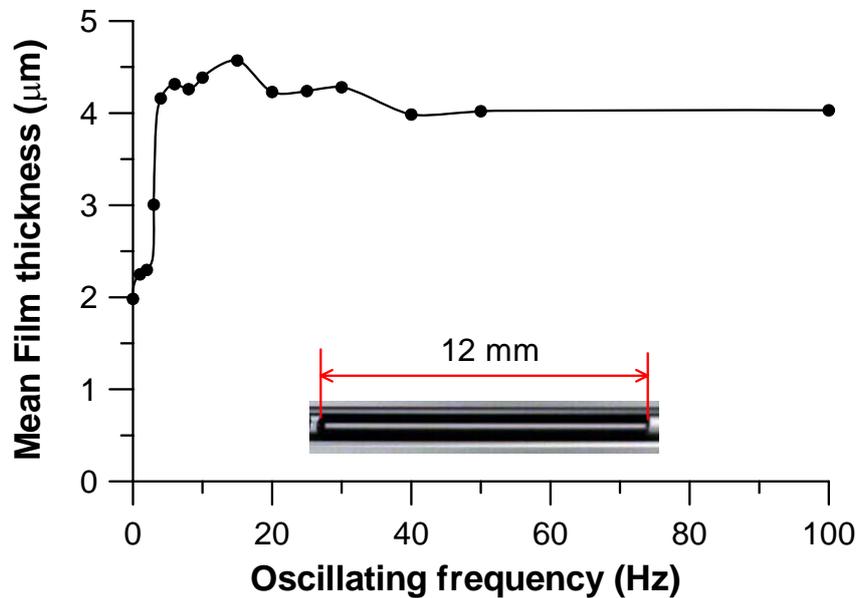


Figure 16 Mean film thickness via oscillating frequency

5. Conclusions

A novel optical method has been developed to measure the interfacial film thickness of a gas plug in a capillary tube. This newly developed method is mainly based on total reflection of incident parallel fringes pattern on the liquid/bubble interface. Utilizing FFT and a Five Point Fitting method (Qiu *et al* 1991) the film thickness can be determined with high resolution. The principles of this method based on geometrical optics and digital image processing technique have been discussed in details. Utilizing the newly developed technique, an air plug bubble oscillating in a horizontal capillary tube with different exciting frequencies has been studied. It is found that the pre-wetted interfacial film thickness could not be zero when the bubble is under static state. Also stepwise film thickness variations have been found when the oscillating frequency changes. Furthermore, when the oscillating frequency reaches to 15Hz, periodical film thickness has been found. Further increasing the oscillating frequency will result in wave-like interfacial film thickness variations. Therefore, current model for interfacial film dynamics should be modified to model the dynamics and surface intermolecular force under oscillating plug flow conditions.

Acknowledgements

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