The Effect of Initial Flow Velocity on the Liquid Film Thickness in Micro Tube Accelerated Slug Flow

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Abstract

Liquid film thickness is an important parameter for predicting boiling and condensation heat transfer in micro tubes. In the present study, the effect of initial flow velocity on the liquid film thickness in accelerated flows under adiabatic condition is experimentally investigated. The laser focus displacement meter is used to measure the initial liquid film thickness. Circular tube with inner diameter of 1 mm was used for the test tube, and water, ethanol and FC-40 are used as working fluids. When the flow is accelerated from small initial velocities under small Bond number condition, initial liquid film thickness is identical to that of steady flow at small capillary numbers, and then deviates from the steady condition and eventually follows that of accelerated flow from zero initial velocity as capillary number is increased. When the flow is accelerated from large initial velocities, initial liquid film thickness deviates from the steady condition earlier and starts to follow that of accelerated flow from zero initial velocity

as capillary number is increased. It is found that the initial flow velocity cannot be neglected in accelerated flows especially at large initial flow velocities and at large Bond numbers. Finally, an empirical correlation is proposed for the initial liquid film thickness of accelerated flows that accounts for the initial flow velocities.

Keywords: Liquid film thickness, Two-phase flow, Micro tube, Acceleration, Initial flow velocity

1. Introduction

Elongated slug flow is one of the representative flow patterns in micro tubes under the flow boiling condition. It is known that the liquid film thickness is one of the key parameters for predicting boiling heat transfer coefficient in micro tubes (Thome et al., 2004). Evaporation heat transfer coefficient through the liquid film in a steady slug flow is represented as follows:

$$h = \frac{k}{\delta} \quad (1)$$

Where h is the heat transfer coefficient, k is the thermal conductivity of the liquid and δ is the liquid film thickness. Many investigations on liquid film thickness in micro tubes have been conducted (Thome et al., 2004; Kenning et al., 2006; Qu & Mudawar, 2004; Saitoh et al., 2007). Taylor (1961) experimentally obtained the mean liquid film thickness deposited on the wall by measuring the difference of the bubble velocity and the mean velocity. It was reported that the liquid film thickness increases with capillary number and reaches a certain fraction of the tube diameter. Taylor's experimental data were correlated by Aussillous & Quere (2000) as a function of capillary number (Ca):

$$\frac{\delta}{D} = \frac{0.67Ca^{2/3}}{1 + 3.35Ca^{2/3}} \quad (2)$$

Han & Shikazono (2009a, b) carried out systematic measurements on liquid film thickness in micro two-phase steady flows under the adiabatic condition using laser focus displacement meter. Predictive correlations for the initial liquid film thickness based on capillary number, Reynolds number and Weber number were proposed. Howard & Walsh (2013) examined the liquid film thickness caused by continuous liquid-gas slug train in a small scale tube for a wide range of capillary numbers using an optical measurement technique. Their experimental data were compared with the existing model proposed by Han & Shikazono (2009a) which can be applied the range

of capillary numbers up to 0.3. It was reported that their experimental data were found to correlate well with the Han & Shikazono model in a wide range of capillary numbers up to 1.9. Under flow boiling in micro two-phase flow, the bubble velocity is not constant but accelerated. It is necessary to consider this acceleration effect on the liquid film thickness (Kenning et al., 2006). Moriyama & Inoue (1996) measured the liquid film thickness formed by a vapor bubble expansion in a narrow gap through temperature change of the channel wall. It was reported that when acceleration becomes large, liquid film thickness is affected by the viscous boundary layer. A predictive correlation was suggested in terms of dimensionless boundary layer thickness, capillary number and Bond number. Han & Shikazono (2010) investigated the effect of acceleration on the liquid film thickness in micro tubes. It was reported that the increase of liquid film thickness with capillary number is restricted by the acceleration. A predictive correlation was proposed for the initial liquid film thickness based on capillary number and Bond number. However, their experiments were limited to cases with zero velocity at the initial state. Qu & Mudawar (2003) investigated flow characteristics of two-phase micro-channel heat sinks in which the highest inlet liquid Reynolds number (Re_0) is 303, corresponding capillary number (Ca_0) is 0.01. Chen et al. (2014) experimentally investigated flow condensation in microchannels in which the inlet vapor Reynolds number (Re_0) ranges from 408 to 1042, correspondingly capillary number (Ca_0) is ranged from 0.03 to 0.076. Considering the real phase change phenomena, liquid and vapor bubbles are supplied to the heating or cooling section with a certain flow velocity. Therefore, it is essential to consider the effect of initial flow velocity on liquid film thickness in accelerated flow.

In the present study, the liquid film thicknesses in accelerated flows under adiabatic condition are experimentally investigated with various initial flow velocities.

The liquid film thickness is measured in a micro circular tube for several working fluids using laser focus displacement meter. The flow visualization using high speed camera is performed to observe the gas-liquid interface shape change. The experimental results are compared with an existing model which does not consider the initial flow velocity and the effect of the initial flow velocity on the liquid film thickness is discussed. Finally, an empirical correlation is proposed for the initial liquid film thickness of accelerated flows that accounts for the initial flow velocities.

2. Experimental setup and procedures

2.1. Experimental setup

A circular tube made of Pyrex glass with inner diameter (D) of 1 mm and length of 500 mm was used for the test tube. Water, ethanol and FC-40 were used as working fluids and air was used as the gas phase. Figure 1 represents the schematic diagram of the experimental setup. Actuator motor (EZHC6A-101, Oriental motor) was used to pull the liquid and to accelerate the flow. Local gas-liquid interface velocity and acceleration were calculated from the image obtained by a high-speed camera (Photron SA1.1). Laser focus displacement meter (LFDM; LT 9010M, Keyence) was used to measure the liquid film thickness. The tube is horizontally oriented. Gas-liquid interface velocities and liquid film thicknesses are measured from the side of the tube. LFDM has been used by several researchers for the measurement of the liquid film thickness (Takamasa & Kobayashi, 2000; Hazuku et al., 2005; Han & Shikazono, 2009a, 2009b, 2010). Figure 2 shows the principle of the LFDM. The position of the target surface can be determined by the displacement of objective lens moved by the tuning fork. The intensity of the reflected light becomes highest in the light-receiving element when the focus is obtained on the target surface. Objective lens is vibrated continually in the

range of ± 0.3 mm. Relative distance between interfaces can be detected during one cycle of the objective lens vibration. The resolution of the present LFDM is 0.01 μm , the laser spot diameter is 2 μm and the response time is 640 μs . Measured liquid film thickness is transformed to DC voltage signal in the range of ± 10 V. Detailed measurement uncertainties can be found in the previous study (Han & Shikazono, 2009a).

2.2. Correction for the tube wall curvature

As the laser beam passes through the tube wall, focus is scattered within a certain range due to the difference of curvatures between axial and azimuthal directions. Cover glass and glycerol were used to remove the curvature effect caused by the outer wall as shown in Fig. 3. Refractive index of glycerol ($n = 1.47$) is almost same with that of the Pyrex glass ($n = 1.474$). Thus, the refraction of laser between glycerol and Pyrex glass can be neglected. Refractive indices of water, ethanol, and FC-40 are 1.33, 1.36, and 1.29. It is difficult to detect the interface between inner wall and liquid, because the difference of the refractive index and the liquid is small. Therefore, the distance from the cover glass to the dry inner wall is initially measured without liquid flow. Then, total thickness of the wall with liquid film is measured. The liquid film thickness is calculated from the difference of these two values. The effect of the inner wall curvature is corrected by the equation suggested by Takamasa & Kobayashi (2000). Figure 4 shows the laser path and refraction through the liquid film. Laser focus is scattered from δ_1 and δ_2 . The intensity of the reflected light becomes highest at the center of δ_1 and δ_2 . Therefore, liquid film thickness δ can be obtained as follows:

$$\delta = \frac{\delta_1 + \delta_2}{2} \quad (3)$$

In Eq. (3), δ_1 and δ_2 are the liquid film thicknesses through Z and X axes, respectively.

Liquid film thickness δ_1 through Z axis can be calculated from Eqs. (4) and (5) as:

$$\delta_1 = y_m \cdot \frac{\tan \theta_w}{\tan \theta_f}, \quad (4)$$

$$\frac{\sin \theta_w}{\sin \theta_f} = \frac{n_f}{n_w}, \quad (5)$$

where n_f and n_w are the refractive indices of the working fluid and the tube wall, respectively. In Eq. (4), y_m is the difference of the distance from the cover glass to the dry inner wall and the thickness with liquid film. y_m can be obtained as the distance of objective lens movement from the recorded data during the experiments. The angle of incidence θ_w is 10.07° in the present laser focus displacement meter. The angle of refraction θ_f is determined from the Snellius' law as Eq. (5). Liquid film thickness δ_2 through X axis can be calculated from Eq. (6) as:

$$\delta_2 = y_0 + \frac{x_0}{\tan(\theta_w - \theta'_w + \theta'_f)}, \quad (6)$$

where θ'_w and θ'_f are the angle of incidence and the angle of refraction in X axis, and (x_0, y_0) is the intersection point between the laser and inner wall in X axis. They are implicitly obtained from the following relations:

$$x_0^2 + y_0^2 = Dy_0, \quad (7)$$

$$y_0 = y_m - \frac{x_0}{\tan \theta_w}, \quad (8)$$

$$x_0 = (D/2) \sin(\theta_w - \theta'_w), \quad (9)$$

$$\frac{\sin \theta'_w}{\sin \theta'_f} = \frac{n_f}{n_w}. \quad (10)$$

From Eqs. (6) – (10), δ_2 is deduced as:

$$\delta_2 = y_m + \frac{1}{2} D \sin(\theta_w - \theta'_w) \cdot \left(\frac{1}{\tan(\theta_w - \theta'_w + \theta'_f)} - \frac{1}{\tan \theta_w} \right) \quad (11)$$

Finally, liquid film thickness δ can be obtained from Eqs. (4) and (11) as follows:

$$\delta = \frac{1}{2} y_m \left(\frac{\tan \theta_w}{\tan \theta_f} + 1 \right) + \frac{1}{4} D \sin(\theta_w - \theta'_w) \cdot \left(\frac{1}{\tan(\theta_w - \theta'_w + \theta'_f)} - \frac{1}{\tan \theta_w} \right) \quad (12)$$

The curvature effect caused by the inner wall is small when the liquid film is thin. The scattering length $(\delta_2 - \delta_1)$ is less than 2% of the liquid film thickness in the present study.

2.3. Physical properties of the working fluids

Three working fluids, water, ethanol, and FC-40 were used. Gas is air and all experiments were conducted under the condition of room temperature and 1 atm. Table 1 shows the properties of three liquids at 20 °C and 25 °C. The liquid temperature was monitored in front of the syringe to ensure accurate thermophysical properties.

2.4. Experimental procedures

The liquid film thickness was measured at several positions as shown in Fig. 5. The gas-liquid interface initially moves with a constant velocity and starts to accelerate at $Z = 0$ mm. For convenience of conducting experiments, positions of LFDM are fixed and initial gas-liquid interface location and acceleration starting point are moved to change the distance to the measuring positions. Local gas-liquid interface velocity at each point is obtained using high speed camera by measuring the movement of the gas-liquid interface. Figure 6 represents time (t) variations of gas-liquid interface velocity (U). The flow is accelerated with uniform acceleration (a) from the initial constant velocity (U_0).

Figure 7 represents measured liquid film thickness variations against time. Liquid film thickness at the tube side is measured under the condition of room temperature and 1 atm. Liquid film thickness shows initial quick decrease and then

decreases monotonically. Initial quick decrease corresponds to the transition region between the bubble nose and the flat film region. If the angle of interface becomes larger than 11° , intensity of the reflected light becomes weak and the interface position cannot be detected by LFDM. Therefore, the whole shape of the bubble nose cannot be measured and the liquid film thickness only after the transition region can be measured (Han & Shikazono, 2009a). When the flow is accelerated, the gas-liquid interface velocity increases along the flow direction. Liquid film thickness becomes thicker as the gas-liquid interface velocity increases along the flow direction. In the present experiment, liquid film thickness is measured at the fixed position. This is the reason why the liquid film thickness decreases gradually after the initial quick decrease even for the accelerated conditions. The thickness just after the initial rapid decrease is defined as the initial liquid film thickness (δ_0) as shown in Fig. 7. This initial liquid film thickness is used for the following experimental data reduction.

The bubble shapes with liquid film are acquired from the high speed camera visualization. Liquid film thickness can be also estimated from the flow visualization images considering the refraction effects of the wall. The location which gives the same initial liquid film thickness value obtained from LFDM is defined as the location of the initial liquid film thickness.

3. Results and discussion

Han & Shikazono (2010) proposed an empirical correlation for the initial liquid film thickness in accelerated flow stagnant conditions as follows:

$$\frac{\delta_0}{D} = \min \left[\left(\frac{\delta_0}{D} \right)_{\text{steady}}, \left(\frac{\delta_0}{D} \right)_{\text{accel}} \right] \quad (13)$$

where subscripts “steady” and “accel” represent steady and accelerated conditions,

respectively. Each correlation is expressed as follows:

$$\left(\frac{\delta_0}{D}\right)_{\text{steady}} = \frac{0.67Ca^{2/3}}{1 + 3.13Ca^{2/3} + 0.504Ca^{0.672} Re^{0.589} - 0.352We^{0.629}}, \quad (14)$$

$$\left(\frac{\delta_0}{D}\right)_{\text{accel}} = \frac{0.968Ca^{2/3}}{Bo^{0.414} + 4.838Ca^{2/3}}. \quad (15)$$

where δ_0 , ρ , a and σ are initial liquid film thickness, liquid density, flow acceleration and surface tension, respectively. In Eqs. (14) and (15), dimensionless numbers of Capillary number $Ca = \mu U/\sigma$, Renolds number $Re = \rho UD/\mu$ and Weber number $We = \rho U^2 D/\sigma$ are used. Bond number Bo based on the flow acceleration a is introduced as follows:

$$Bo = \frac{\rho a D^2}{\sigma} \quad (16)$$

Equation (14) is valid only for laminar flow. Re_{critical} is critical Reynolds number at which flow changes from laminar to turbulent. $Re_{\text{critical}} = 2200$ is used in [Han & Shikazono \(2009a\)](#). The accelerated flow Eq. (15) is obtained from the experiments of zero initial flow velocity, which is different from the conditions in the present study.

3.1. Water/air experiment

Figures 8(a) and (b) show dimensionless initial liquid film thickness against capillary number for various initial flow velocities using water. Each symbol represents initial liquid film thickness data taken at different distances from the acceleration starting point for same initial velocity. Initial flow velocity (U_0) is non-dimensionalized as initial capillary number $Ca_0 = \mu U_0/\sigma$. The data at initial steady flow velocity (Ca_0) are shown with steady thickness prediction, Eq. (14). The initial liquid film thicknesses under the acceleration are compared to [Eq. \(13\)](#) which is developed for flows accelerated from zero initial flow velocity. Figure 8(a) represents dimensionless initial

liquid film thickness variations at $Bo = 1.4$. It can be seen that the initial liquid film thickness for each initial flow velocity is identical to the steady thickness prediction. At small capillary numbers, initial liquid film thickness is identical to the steady thickness prediction, Eq. (14). As capillary number increases, initial liquid film thickness deviates from the steady prediction line and becomes much thinner. In the previous study of [Han & Shikazono \(2010\)](#), it was concluded that the increase of initial liquid film thickness with capillary number is restricted by the acceleration. As the flow is accelerated from small initial velocity ($Ca_0 = 0.003$), the initial liquid film thickness can be well predicted by Eq. (13), which means that the initial flow velocity effect is small. As the initial steady flow velocity increases, the initial liquid film thickness starts to deviate from Eq. (13). As the flow is accelerated from large initial velocity ($Ca_0 = 0.023$), the initial liquid film thickness remains nearly unchanged against capillary number, which is significantly thicker than Eq. (13). Thus, the initial flow velocity effect becomes significant at large initial flow velocity. However, as capillary number increases, initial liquid film thickness follows again Eq. (13) regardless of the initial flow velocities, and the initial flow velocity effect becomes negligible. Figure 8(b) represents dimensionless initial liquid film thickness variations at $Bo = 2.7$. For larger Bond number, i.e. larger acceleration condition, deviation from the steady line starts from smaller capillary number. Larger Bond number data shows significant deviations from Eq. (13). Thus, the effect of initial flow velocity becomes significant with increasing initial flow velocity and acceleration. At a fixed capillary number in the region where the initial flow velocity effect becomes apparent, initial liquid film is thicker for larger initial flow velocities. At large capillary numbers, the initial flow velocity effect again becomes small and the initial liquid film thickness follows Eq. (13) even for large initial flow velocity and acceleration conditions.

Figures 9(a) and (b) show gas-liquid interface shape variations against capillary number at large acceleration case, $Bo = 2.7$. At small initial flow velocity ($Ca_0 = 0.003$), the interface shape gradually becomes slender with capillary number. At large initial flow velocity ($Ca_0 = 0.023$), the interface radius size remains nearly unchanged and then becomes gradually slender as capillary number is increased. The measurement locations of the initial liquid film thickness (δ_0) are represented as red triangles in Fig. 9 which give the same initial liquid film thickness values obtained from LFDM. The locations of the initial liquid film thickness are defined as the end of the transition region before the flat film region. When the capillary number is small, the location of the initial liquid film thickness is close to the bubble nose. As the capillary number is increased, the location of the initial liquid film thickness gradually moves away from the bubble nose.

3.2. Ethanol/air experiment

Figures 10(a) and (b) show dimensionless initial liquid film thickness against capillary number for the ethanol/air experiment. For the ethanol/air case, initial liquid film thickness start to deviate from the steady prediction line right after the flow is accelerated. When the flow is accelerated from large initial velocity ($Ca_0 = 0.071$), the initial liquid film thickness remains nearly constant against capillary number, which is significantly thicker than Eq. (13). For large capillary numbers, the initial liquid film thicknesses asymptote to a constant thickness regardless of the initial flow velocity. Aussillous & Quere (2000) reported that the confinement effect makes the film thickness converge to a finite fraction of the tube radius at large capillary numbers in capillary slug flow. It is considered that the confinement due to tube geometry limits the liquid film thickness not only for steady flows but also for accelerated flows. More detailed explanation for the confinement effect is described in section 3.4.

Figure 11 shows gas-liquid interface shape variations against capillary number at $Bo = 3.87$. Red triangles represent the measurement positions of the initial liquid film thickness. At small initial flow velocity ($Ca_0 = 0.011$), the interface shape gradually becomes slender, and then remains unchanged as capillary number is increased. At large initial flow velocity ($Ca_0 = 0.071$), the interface shape slightly becomes slender with capillary number, and then remains nearly unchanged.

3.3. FC-40/air experiment

Figures 12(a) and (b) show dimensionless initial liquid film thickness against capillary number for FC-40/air experiment. As the flow is accelerated from small initial velocity ($Ca_0 = 0.007$), the initial liquid film thickness is well predicted by Eq. (13) and then the initial liquid film thickness reaches an upper limit. As the flow is accelerated from large initial velocity ($Ca_0 = 0.187$), the initial liquid film maintains its thickness and there is no change in the initial liquid film thickness against capillary number. As in the case of ethanol/air experiment, the initial liquid film thicknesses for large capillary numbers asymptote to a constant thickness regardless of the initial flow velocity.

Figures 13(a) and (b) show gas-liquid interface shape variations against capillary number for $Bo = 11.6$. At small initial flow velocity ($Ca_0 = 0.06$), the interface shape gradually becomes slender, and then remains unchanged with capillary number. At large initial flow velocity ($Ca_0 = 0.187$), the gas-liquid interface shape maintains its initial shape, and then slightly shrinks, and becomes nearly unchanged again as capillary number is increased.

3.4. Confinement effect due to tube geometry

For ethanol/air experiment and FC-40/air experiment, convergence of the

initial liquid film thickness to a constant value was observed at large capillary numbers. [Aussillous & Quere \(2000\)](#) proposed a simple criterion for the limit in capillary number, Ca^{**} , above which the liquid film thicknesses converge to a finite fraction of the tube radius due to confinement effect in capillary slug flow as follows:

$$Ca^{**} \sim \left(\frac{\mu^2}{\sigma \rho D} \right)^{1/2}. \quad (17)$$

The dimensionless number, $\mu^2/\sigma \rho D$ is a function of liquid property and tube diameter. Based on the present experimental data, the criterion for the limit in capillary number, Ca^{**} for accelerated flow is correlated in the form as:

$$Ca^{**} = 19.8 \left(\frac{\mu^2}{\sigma \rho D} \right)^{1/2}. \quad (18)$$

The value of 19.8 in Eq. (18) is just fitted to represent well the present experimental data. From Eq. (18), the confinement limit capillary number values for water, ethanol, and FC-40 are 0.073, 0.176, and 0.417, respectively. The values of Ca^{**} obtained from Eq. (18) for ethanol and FC-40 are represented in Figs. 10 and 12. It can be seen that Eq. (18) well predicts the capillary number limit above which the initial liquid film thicknesses converge to a constant thickness. The value of Ca^{**} for water, 0.073 is beyond the capillary number range ($Ca < 0.06$) of the present water/air experiment. Therefore, the confinement effect is not observed in the water/air experiment.

3.5. Predictive correlation in accelerated flows with non-zero initial velocities

When the initial flow velocity effect becomes significant, Eq. (13) for zero initial velocity condition becomes invalid. Therefore, new correlation is necessary which accounts for the effects of initial flow velocity. The improved correlation considering initial flow velocity is proposed as follows:

(i) $Ca < Ca^{**}$

$$\frac{\delta_0}{D} = \begin{cases} \min \left[\left(\frac{\delta_0}{D} \right)_{\text{steady}}, \left(\frac{\delta_0}{D} \right)_{\text{accel}} \right] & (\delta_0 / D)_{\text{steady at } Ca_0} < (\delta_0 / D)_{\text{accel at } Ca_0} \\ \max \left[\left(\frac{\delta_0}{D} \right)_{\text{steady at } Ca_0}, \left(\frac{\delta_0}{D} \right)_{\text{accel}} \right] & (\delta_0 / D)_{\text{steady at } Ca_0} > (\delta_0 / D)_{\text{accel at } Ca_0} \end{cases} \quad (19)$$

(ii) $Ca > Ca^{**}$

$$\frac{\delta_0}{D} = \left(\frac{\delta_0}{D} \right)_{\text{accel at } Ca^{**}} \quad (20)$$

where Eq. (14) is used for $(\delta_0 / D)_{\text{steady}}$, Eq. (15) is used for $(\delta_0 / D)_{\text{accel}}$, and Eq. (18) is used for Ca^{**} . Subscripts “steady at Ca_0 ” and “accel at Ca_0 ” represent steady condition and accelerated condition based on the initial flow velocity (Ca_0). Subscript “accel at Ca^{**} ” represents accelerated condition based on the confinement limit capillary number (Ca^{**}). Figure 14 explains the correlation in detail using water/air experimental data. Figure 15 shows the comparison between the experimental data and the prediction from Eqs. (19) and (20) against capillary number. Equations (19) and (20) can predict liquid film thickness very accurately for three working fluids. Figure 16 shows the comparison of present correlation, Equations (19) and (20), with the experimental data. Present correlation can predict the liquid film thickness accurately within the range of 15% accuracy.

4. Conclusions

The initial liquid film thicknesses in accelerated micro two phase flows with various initial flow velocities were experimentally investigated. The initial flow velocity effect cannot be neglected in accelerated flows at large initial flow velocities and at large Bond numbers. When the flow is accelerated from small initial velocities under small Bond number condition, initial liquid film thickness is identical to that of steady

flow at small capillary numbers, and then deviates from the steady condition and eventually follows that of accelerated flow from zero initial velocity as capillary number is increased. When the flow is accelerated from large initial velocities, initial liquid film thickness deviates from the steady condition earlier and starts to follow that of accelerated flow from zero initial velocity as capillary number is increased. It is found that the initial flow velocity cannot be neglected in accelerated flows especially at large initial flow velocities and at large Bond numbers. Experimental correlation for the initial liquid film thickness of accelerated flows that accounts for initial flow velocity is proposed. In order to develop precise flow boiling models in a micro tube where the flow is accelerated, it is necessary to consider the effect of initial flow velocity on the initial liquid film thickness.

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5. References

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Table. 1. Properties of the working fluids at 20 °C and 25 °C.

	Temperature (°C)	Water	Ethanol	FC-40
ρ (kg/m ³)	20	998	789	1860
	25	997	785	1849
μ (μPa s)	20	1001	1196	3674
	25	888	1088	3207
σ (mN/m)	20	72.7	22.8	16.3
	25	72.0	22.3	15.9
n		1.33	1.36	1.29

Fig. 1. Schematic diagram of the experimental setup.

Fig. 2. Principle of the laser focus displacement meter.

Fig. 3. Correction for the outer wall curvature.

Fig. 4. Correction for the inner wall curvature.

Fig. 5. Initial gas-liquid interface location and measuring points.

Fig. 6. Gas-liquid interface velocity against time, ethanol, $D = 1$ mm, $U_0 = 263$ mm/s, $a = 165$ m/s².

Fig. 7. Liquid film thickness variations against time, ethanol, $D = 1$ mm, $U = 2.47$ m/s (at $t = 0.005$ s) and $a = 165 \text{ m/s}^2$.

(a) $Bo = 1.4$ ($a = 101$ m/s²)

(b) $Bo = 2.7$ ($a = 195$ m/s²)

Fig. 8. Dimensionless initial liquid film thickness (δ_0/D) against capillary number (Ca) at different initial flow velocities (Ca_0) for the water/air experiment, (a) $Bo = 1.4$ ($a = 101$ m/s²), (b) $Bo = 2.7$ ($a = 195$ m/s²).

(a) $Ca_0 = 0.003$

(b) $Ca_0 = 0.023$

Fig. 9. Gas-liquid interface shapes and location of initial liquid film thickness (δ_0) at $Bo = 2.7$ ($a = 195 \text{ m/s}^2$) for water/air experiment, (a) $Ca_0 = 0.003$, (b) $Ca_0 = 0.023$.

(a) $Bo = 3.87$ ($a = 108 \text{ m/s}^2$)

(b) $Bo = 5.98$ ($a = 165 \text{ m/s}^2$)

Fig. 10. Dimensionless initial liquid film thickness (δ_0/D) against capillary number (Ca) at different initial flow velocities (Ca_0) for the ethanol/air experiment, (a) $Bo = 3.87$ ($a = 108 \text{ m/s}^2$), (b) $Bo = 5.98$ ($a = 165 \text{ m/s}^2$).

(a) $Ca_0 = 0.011$

(b) $Ca_0 = 0.071$

Fig. 11. Gas-liquid interface shapes and location of initial liquid film thickness (δ_0) at $Bo = 3.87$ ($a = 108 \text{ m/s}^2$) for ethanol/air experiment, (a) $Ca_0 = 0.011$, (b) $Ca_0 = 0.069$.

(a) $Bo = 11.6$ ($a = 100 \text{ m/s}^2$)

(a) $Bo = 18.6$ ($a = 160 \text{ m/s}^2$)

Fig. 12. Dimensionless initial liquid film thickness (δ_0/D) against capillary number (Ca) at different initial flow velocities (Ca_0) for the FC-40/air experiment, (a) $Bo = 11.6$ ($a = 100 \text{ m/s}^2$), (b) $Bo = 18.6$ ($a = 160 \text{ m/s}^2$).

(a) $Ca_0 = 0.060$

(b) $Ca_0 = 0.187$

Fig. 13. Gas-liquid interface shapes and location of initial liquid film thickness (δ_0) at $Bo = 11.6$ ($a = 100 \text{ m/s}^2$) for FC-40/air experiment, (a) $Ca_0 = 0.060$, (b) $Ca_0 = 0.187$.

(a)

(b)

Fig. 14. Prediction of Eq. (19),

(a) Decomposition of the model, (b) final prediction.

(a) Water

(b) Ethanol

(c) FC-40

Fig. 15. Predicted initial liquid film thickness (δ_0/D) against capillary number (Ca),
(a) Water, (b) Ethanol, and (c) FC-40.

Fig. 16. Comparison between predicted values from Eqs. (19) and (20) and experimental data.