The Effect of Bubble Deceleration on the Liquid Film Thickness in Micro Tubes

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Abstract

Liquid film thickness is an important parameter for predicting boiling and condensation heat transfer coefficients in micro tube slug flows. In the present study, the effect of bubble deceleration on the liquid film thickness is experimentally investigated under adiabatic condition. The laser focus displacement meter is used to measure the liquid film thickness. Circular tubes with three different inner diameters, $D = 0.7, 1.0$ and 1.3 mm, are used. Measurement is carried out using a micro tube with one open end and the other connected to an actuator motor. Water, ethanol and FC-40 are used as working fluids. It is found that deceleration makes the liquid film thicker than that in the steady flow, and it deviates from the steady case as the deceleration rate is increased. Liquid film thickness remains nearly unchanged just after the onset of deceleration, and then gradually decreases and eventually converges to the steady thickness as the velocity is further decreased. Finally, an empirical correlation is proposed to predict

initial liquid film thickness in decelerated flows.

Keywords: Liquid film thickness, Two-phase flow, Micro tube, Deceleration

Nomenclature

a	flow deceleration (m/s^2)
Bo	Bond number based on flow deceleration, $Bo = \rho a D^2 / \sigma$
Ca	capillary number, $Ca = \mu U / \sigma$
D	tube inner diameter (m)
h	heat transfer coefficient ($\text{W/m}^2\text{-K}$)
k	thermal conductivity (W/m-K)
n	refractive index
Re	Reynolds number, $Re = \rho U D / \mu$
t	time (s)
U	flow velocity (m/s)
We	Weber number, $We = \rho U^2 D / \sigma$
Z	axial distance from the decelerating start-point (m)

Greek symbols

δ	liquid film thickness (m)
λ	transition region length (m)
μ	viscosity (Pa s)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

0	initial
1	through Z axis in Fig. 4
2	through X axis in Fig. 4

decel decelerated condition

steady steady condition

1. Introduction

Slug flow is one of the representative flow patterns in micro tube two phase flows, which is important in many thermal and chemical engineering applications such as heat pipes and micro reactors, etc. It is known that the liquid film thickness is one of the key parameters for predicting flow boiling and flow condensation heat transfer coefficients in micro tubes (Thome et al., 2004; Qu & Mudawar, 2004; Kenning et al., 2006; Saitoh et al., 2007; Wu et al., 2010; Odaymet et al., 2012). Evaporation or condensation heat transfer coefficient through the liquid film in a steady laminar 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. Taylor (1961) experimentally obtained the mean liquid film thickness by measuring the difference between mean and bubble velocities. It was reported that the liquid film thickness increases with capillary number and asymptotes to a certain fraction of the tube diameter. Taylor's experimental data were correlated by Aussillous & Quere (2000) as a function of capillary number Ca as follows:

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

In a steady slug flow, Han & Shikazono (2009a, b) carried out systematic measurements on liquid film thickness under the adiabatic condition using laser focus displacement meter. Predictive correlations for the initial liquid film thickness based on capillary number Ca , Reynolds number Re and Weber number We were proposed. On the other hand, under flow boiling in micro two-phase flow, the bubble velocity is not constant but accelerated, and the flow pattern becomes very complicated (Kenning et al.,

2006; Rao et al., 2013; Rao et al., 2015). Moriyama & Inoue (1996) measured the thickness of the liquid film formed by a vapor bubble expansion in a narrow gap. It was reported that liquid film thickness is affected by the viscous boundary layer in the preceding liquid flow. Their experimental data was correlated in terms of dimensionless boundary layer thickness, capillary number and Bond number based on flow acceleration. Han & Shikazono (2010) investigated the effect of acceleration on the liquid film thickness in micro tubes. It was reported that the liquid film thickness becomes thinner than the steady case under flow acceleration. New correlation for the initial liquid film thickness in accelerated condition was proposed. However, their experiments were limited to cases with zero velocity at the initial state. Youn et al. (2015) and Muramatu et al. (2015) experimentally and numerically investigated the effect of initial flow velocity on the liquid film thickness in accelerated flows. It was found that the effect of initial flow velocity cannot be neglected in accelerated flows especially at large initial flow velocities and large acceleration Bond numbers. A predictive correlation was proposed for the initial liquid film thickness of accelerated flows that takes into account the initial flow velocity effect.

On the other hand, the bubble velocity is decelerated in two-phase flows with condensation. For example, it is important to consider both acceleration and deceleration effects on the liquid film thickness in oscillating heat pipes (Rao et al., 2013; Rao et al., 2015). In the present study, the effect of bubble deceleration on the liquid film thickness in micro tubes under adiabatic condition is experimentally investigated. The liquid film thickness in micro circular tubes is measured using laser focus displacement meter for three different working fluids, i.e. water, ethanol and FC-40. The flow visualization using high speed camera is carried out to observe the bubble shape change. Finally, an empirical correlation is proposed to predict initial

liquid film thickness in decelerated micro tube slug flows.

2. Experimental setup and procedures

2.1. Experimental setup

Circular tubes made of Pyrex glass with inner diameter of $D = 0.7, 1.0$ and 1.3 mm were used as test tubes. Water, ethanol and FC-40 were used as working fluids and air was used as the gas phase. Tube length is 500 mm for 0.7 and 1.0 mm tubes and 700 mm for 1.3 mm tube to ensure fully developed flows before deceleration. Figure 1 represents the schematic diagram of the experimental setup. Actuator motor (EZHC6A-101, Oriental motor) was used to pull the liquid and to decelerate the flow. Instantaneous bubble velocities and deceleration rates were obtained from the images 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, and the instantaneous bubble velocities and liquid film thicknesses are measured from the side of the tube. LFDM has been already used by several researchers to measure liquid film thickness (Takamasa & Kobayashi, 2000; Hazuku et al., 2005; Han & Shikazono, 2009a, 2009b, 2010; Youn et al., 2015). Figure 2 shows the principle of the LFDM. The position of the target surface can be determined by the displacement of objective lens connected to the tuning fork. The intensity of the reflected light in the light-receiving element becomes the highest 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 $0.01 \mu\text{m}$, the laser spot diameter is $2 \mu\text{m}$ and the response time is $640 \mu\text{s}$. Measured liquid film thickness is transformed to DC voltage signal in the range of ± 10 V. Details of the measurement 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 affected by 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 ($n = 1.470$) is almost the 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, respectively. It is difficult to detect the interface between the inner wall and the 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 flowing the liquid. 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 \(2000\)](#) as follows. Figure 4 shows the laser path and refraction through the liquid film. Laser focus scatters from δ_1 and δ_2 , where δ_1 and δ_2 are the liquid film thicknesses through Z and X axes, respectively. The intensity of the reflected light is assumed to become the highest at the center of δ_1 and δ_2 . Therefore, liquid film thickness δ can be obtained as follows:

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

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. Refer to ([Han & Shikazono, 2009a](#); [Youn et al., 2015](#)) for the details.

2.3. Physical properties of the working fluids

Three working fluids, water, ethanol and FC-40 were used. Gas phase 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 bubble front is initially moving with a constant velocity and starts to decelerate at $Z = 0$. The liquid film thickness was measured at several distances from the deceleration starting position, $Z = 0$, as shown in Fig. 5. For the convenience of conducting the experiments, LFD position is fixed and initial bubble front location and deceleration starting point are moved to change the distance of measurement Z . Instantaneous bubble velocity at each point is obtained using high speed camera by measuring the movement of the bubble front. Figure 6 shows an example of time variations of instantaneous bubble velocity U . The flow is decelerated with uniform deceleration rate 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. 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 the LFD. 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). The thickness just after the initial

rapid decrease is defined as the initial liquid film thickness δ_0 as shown in Fig. 7 (Han & Shikazono, 2009a, 2009b, 2010; Youn et al., 2015).

3. Results and discussions

3.1. Water/air experiment

Figures 8(a)–(c) show the dimensionless initial liquid film thicknesses against capillary number for the water/air experiment. Each symbol represents the initial liquid film thickness data for the same initial velocity and deceleration rate. The steady initial liquid film thickness data are also represented as an open symbol in the figure. Initial bubble velocity U_0 and instantaneous bubble velocity U are non-dimensionalized as initial capillary number $Ca_0 = \mu U_0 / \sigma$ and instantaneous capillary number $Ca = \mu U / \sigma$, respectively. In order to express the bubble deceleration effect, Bond number based on the bubble deceleration rate is introduced as follows:

$$Bo_{\text{decel}} = \frac{\rho |a| D^2}{\sigma} \quad (4)$$

where a is the bubble deceleration rate. Note that the absolute value of a is used for the Bond number, i.e. $Bo_{\text{decel}} > 0$.

At small capillary numbers, the initial liquid film thickness is identical to the data under steady condition. The effect of deceleration on the liquid film thickness is negligible. This feature is also found under acceleration condition, i.e. acceleration effect becomes negligible at small capillary numbers and the liquid film thickness depends only on capillary number (Han & Shikazono, 2010; Youn et al., 2015). In Fig. 8, at large capillary numbers, liquid film thickness deviates from the data under steady condition and liquid film thickness is much larger. For larger deceleration Bond numbers, i.e. larger deceleration rates, deviation from the steady condition becomes

significant and deviation starts from smaller capillary numbers. It is shown that the deceleration makes the liquid film thicker than that in the steady flow. For a fixed Bond number, initial liquid film thickness remains nearly unchanged just after the onset of deceleration, and then gradually decreases and eventually converges to the steady condition as the capillary number is decreased.

In the accelerated flow, the initial liquid film thickness remains nearly constant just after the onset of acceleration and then follows the line of accelerated flow from zero velocity (Youn et al., 2015). When the flow is accelerated, the Stokes boundary layer is induced in the liquid slug and the instantaneous velocity profile can be given by superposition of the Stokes layer and the initial parabolic velocity profile of a steady flow. Due to the flow acceleration, the velocity gradient gets steeper near the wall compared to the steady flow, and the change of the velocity profile makes the viscous boundary layer in the liquid slug thinner, which results in thinner liquid film (Muramatsu et al., 2015).

It is considered that the deceleration makes the velocity gradient smaller near the wall, which results in thicker viscous boundary layer and thicker liquid film. Figure 9 shows the dimensionless initial liquid film thickness against capillary number with different Bond numbers under a fixed initial capillary number ($Ca_0 = 0.018$). Larger Bond number data, i.e. larger deceleration rate, show significant deviation from the steady condition. At a fixed instantaneous capillary number in the region where the deceleration effect is apparent, the initial liquid film is thicker for larger deceleration Bond number and larger initial capillary number. For very small Bond numbers, the initial liquid film thickness is identical to that of the steady condition.

Figure 10 shows the time variation of the bubble shape under deceleration rate of $Bo = 5.19$ from initial velocity of $Ca_0 = 0.022$ in a 1.3 mm tube. The liquid film

region remains nearly unchanged, but the bubble nose gradually becomes flat as the flow is decelerated, in the instantaneous capillary number range of $Ca = 0.022 \sim 0.012$. When the bubble nose becomes nearly flat at very low capillary numbers ($Ca = 0.010 \sim 0.002$), the bubble nose is expanded in the radial direction which makes the liquid film significantly thin. Thus, the deceleration first affects the bubble nose shape and then finally affects the liquid film region as the flow is decelerated. The bubble shape change corresponds well with the measured liquid film thickness behaviors shown in Fig. 8(a).

3.2. Ethanol/air experiment

Figures 11(a)–(c) show the dimensionless initial liquid film thicknesses against capillary number for the ethanol/air experiment. As in the case of water/air experiment, initial liquid film thickness becomes identical to the steady condition data at small capillary numbers. As capillary number increases, the liquid film thickness deviates from the steady condition data. For ethanol/air experiment, the obtained maximum Bond number ($Bo = 10.7$) is larger than that of water/air experiment ($Bo = 5.19$). Therefore, initial liquid film thickness deviates from the steady line from lower capillary number.

Figure 12 shows the time variations of the bubble shape under the deceleration rate of $Bo = 10.7$ from initial velocity of $Ca_0 = 0.062$ in a 1.3 mm tube. As in the case of water/air experiment, the bubble nose gradually becomes flat as the flow is decelerated ($Ca = 0.062 \sim 0.028$), and bubble nose is expanded in the radial direction which makes the liquid film significantly thin as capillary number is further decreased ($Ca = 0.017 \sim 0.005$). The flattened bubble nose shape is more clearly observed in the ethanol/air experiment than in the case of water/air experiment, which can be attributed to the larger Bond number. The bubble shape change corresponds well with the measured

liquid film thickness behaviors shown in Fig. 11(a).

3.3. FC-40/air experiment

Figures 13(a)–(c) show the dimensionless initial liquid film thicknesses against capillary number for the FC-40/air experiment. As in the case of water/air and ethanol/air experiments, initial liquid film becomes identical to the steady condition data at small capillary numbers. As capillary number increases, the liquid film thickness deviates from the steady condition data.

Figure 14 shows the time variations of the bubble shape under deceleration rate of $Bo = 9.82$ from initial velocity of $Ca_0 = 0.122$ in a 1.3 mm tube. As in the case of water/air experiment and ethanol/air experiment, the bubble nose gradually becomes flat as the flow is decelerated ($Ca = 0.122 \sim 0.090$) and bubble nose is expanded in the radial direction which makes the liquid film significantly thin as the flow is further decelerated ($Ca = 0.055 \sim 0.005$). The bubble shape change corresponds well with the measured liquid film thickness behaviors shown in Fig. 13(a).

3.4. Scaling analysis for the liquid film under deceleration

Han & Shikazono (2009a) carried out a scaling analysis of the liquid film thickness in steady flows based on Aussillous' analysis (Aussillous & Quere, 2000). The momentum balance and the curvature matching between the bubble nose and the transition region are expressed as follows:

$$\frac{\mu U}{\delta_0^2} \sim \frac{1}{\lambda} \left\{ \frac{\sigma(1+f(\text{Re}, Ca))}{D - \delta_0} \right\} - \frac{1}{\lambda} \rho U^2, \quad (5)$$

$$\frac{\delta_0}{\lambda^2} \sim \frac{(1+f(\text{Re}, Ca))}{D - \delta_0}, \quad (6)$$

where λ is the transition region length as shown in Fig. 15. The expression for dimensionless initial liquid film thickness, δ_0/D is deduced as follows:

$$\frac{\delta_0}{D} \sim \frac{Ca^{2/3}}{Ca^{2/3} + 1 + f(\text{Re}, Ca) - g(We')}. \quad (7)$$

Based on Eq. (16), prefactors and exponents are fitted using their experimental data as follows:

$$\frac{\delta_0}{D} = \frac{0.67Ca^{2/3}}{3.13Ca^{2/3} + 1 + 0.504Ca^{0.672} \text{Re}^{0.589} - 0.352We^{0.629}}. \quad (8)$$

As shown in Fig. 16, Eq. (8) tends to overpredict the present steady experimental data. Therefore, the prefactors and exponents in Eq. (8) are slightly modified so as to fit the present data as follows:

$$\frac{\delta_0}{D} = \frac{0.67Ca^{2/3}}{3.63Ca^{2/3} + 1 + 0.534Ca^{0.672} \text{Re}^{0.589} - 0.352We^{0.640}}. \quad (9)$$

Eq. (9) can predict present liquid film thickness data under steady condition more accurately especially at larger capillary numbers.

Figure 15 shows the schematic diagram of the velocity profiles under steady and decelerated conditions. Under decelerated condition, bubble nose curvature is affected by the viscous boundary layer. It is considered that this velocity profile change in the liquid slug should affect the bubble shape and the liquid film thickness downstream. Therefore, the bubble nose curvature under the bubble deceleration condition is modified as:

$$\kappa \sim \frac{(1 + f(\text{Re}, Ca))}{D - \delta_0} \cdot c, \quad (10)$$

where c is the modification coefficient for the velocity profile change in the liquid slug under decelerated condition. If the curvature of bubble nose in the RHS of Eq. (5) and Eq. (6) is replaced by Eq. (10), Eq. (7) can be rewritten as follows:

$$\frac{\delta_0}{D} \sim \frac{Ca^{2/3}}{Ca^{2/3} + c \cdot (1 + f(Re, Ca)) \left[1 - \frac{We'}{c \cdot (1 + f(Re, Ca))} \right]^{2/3}}. \quad (11)$$

If we assume that the terms of Re , Ca and We are small, we may simplify Eq.

(11) using Taylor expansion as:

$$\frac{\delta_0}{D} \sim \frac{Ca^{2/3}}{Ca^{2/3} + \left[1 + f(Re, Ca) - \frac{g(We')}{c} \right] \cdot c}. \quad (12)$$

When $c = 1$, Eq. (12) should be identical to the steady correlation, Eq. (9).

Therefore, we obtain the following equation:

$$\frac{\delta_0}{D} \sim \frac{0.67Ca^{2/3}}{3.63Ca^{2/3} + \left(1 + 0.534Ca^{0.672} Re^{0.593} - 0.352 \frac{We^{0.640}}{c} \right) \cdot c}. \quad (13)$$

Explicit form of the modification coefficient c can be expressed from Eq. (13)

as:

$$c \sim \frac{0.67Ca^{2/3} / (\delta_0 / D) - 3.63Ca^{2/3} + 0.352We^{0.640}}{1 + 0.534Ca^{0.672} Re^{0.593}}. \quad (14)$$

This dimensionless modification coefficient c is expected to be related to a dimensional parameter which represents the deceleration effect. Figure 17 shows the relationship between the RHS of Eq. (14) and the deceleration Bond number, Eq. (4). Only the experimental data that is not subjected to the initial flow velocity effect are used. In other words, the constant thickness data just after the onset of deceleration are not shown in Fig. 17. As can be seen from the figure, the modification coefficient c can be scaled very well by deceleration Bond number. All the data in the Fig. 17 are well correlated with a single fitting line as:

$$c = \exp(-0.02Bo_{\text{decel}}^{1.45}). \quad (15)$$

Substituting Eq. (15) in Eq. (13), a correlation for the initial liquid film

thickness under bubble deceleration can be obtained as follows:

$$\left(\frac{\delta_0}{D}\right)_{\text{decel}} = \frac{0.67Ca^{2/3}}{3.63Ca^{2/3} - 0.352We^{0.640} + \left(1 + 0.534Ca^{0.672} Re^{0.593}\right)\left(e^{-0.02Bo_{\text{decel}}^{1.45}}\right)}. \quad (16)$$

As shown in Figs. 9, 11 and 13, the initial liquid film thickness remains nearly unchanged just after the onset of deceleration against capillary number. Considering the initial flow velocity effect, the initial liquid film thickness in the whole capillary number range can be simply expressed as follows:

$$\frac{\delta_0}{D} = \min \left[\left(\frac{\delta_0}{D}\right)_{\text{decel}}, \left(\frac{\delta_0}{D}\right)_{\text{steady at } Ca_0} \right], \quad (17)$$

where Eq. (9) is used for $(\delta_0 / D)_{\text{steady}}$ and Eq. (16) is used for $(\delta_0 / D)_{\text{decel}}$. Subscripts “steady at Ca_0 ” represents steady liquid film thickness at initial capillary number (Ca_0). Figure 18 shows the comparison between the experimental data and the prediction by Eq. (17) against capillary number. Equation (17) can predict liquid film thickness very accurately for all conditions. Figure 19 shows the comparison of present correlation with the experimental data. Present correlation can predict the liquid film thickness accurately within the range of 15% accuracy.

4. Conclusions

The effect of bubble deceleration on the liquid film thickness in micro tubes was investigated. When the flow is decelerated, liquid film thickness remains nearly unchanged just after the onset of deceleration, and then gradually decreases and eventually converges to the steady liquid film thickness as the capillary number is further decreased. Deceleration makes the liquid film thicker than that in the steady flow, and it deviates from the steady condition as the deceleration rate is increased. Experimental correlation for the initial liquid film thickness under bubble deceleration

was proposed by modifying the curvature of the bubble nose using deceleration Bond number. The proposed correlation can predict the initial liquid film thickness within the range of 15% accuracy.

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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. An example of gas-liquid interface velocity against time (Ethanol, $D = 1$ mm, $U_0 = 1500$ mm/s, $a = -76.7$ m/s²).

Fig. 7. An example of liquid film thickness variations against time (Ethanol, $D = 1 \text{ mm}$, $U = 1.35 \text{ m/s}$, $a = -76.7 \text{ m/s}^2$).

(a) $D = 1.3$ mm

(b) $D = 1.0$ mm

(c) $D = 0.7$ mm

Fig. 8. Dimensionless initial liquid film thickness (δ_0/D) against capillary number (Ca) at different initial flow velocities (Ca_0) and deceleration Bond numbers (Bo) for the water/air experiment,
(a) $D = 1.3$ mm, (b) $D = 1.0$ mm and (c) $D = 0.7$ mm

Fig. 9. Dimensionless initial liquid film thickness (δ_0/D) against capillary number (Ca) at different deceleration Bond numbers (Bo) under fixed initial flow velocity (Ca_0) for the water/air experiment.

Fig. 10. Time variation of the bubble shapes under deceleration of $Bo = 5.19$ ($a = -220 \text{ m/s}^2$) from $Ca_0 = 0.022$ in a 1.3 mm tube for water/air experiment.

(a) $D = 1.3$ mm

(b) $D = 1.0$ mm

(c) $D = 0.7$ mm

Fig. 11. Dimensionless initial liquid film thickness (δ_0/D) against capillary number (Ca) at different initial flow velocities (Ca_0) and deceleration Bond numbers (Bo) for the ethanol/air experiment,
(a) $D = 1.3$ mm, (b) $D = 1.0$ mm and (c) $D = 0.7$ mm

Fig. 12. Time variation of the bubble shapes under deceleration of $Bo = 10.7$ ($a = -180 \text{ m/s}^2$) from $Ca_0 = 0.062$ in a 1.3 mm tube for ethanol/air experiment.

(a) $D = 1.3$ mm

(b) $D = 1.0$ mm

(c) $D = 0.7$ mm

Fig. 13. Dimensionless initial liquid film thickness (δ_0/D) against capillary number (Ca) at different initial flow velocities (Ca_0) and deceleration Bond numbers (Bo) for the FC-40/air experiment,
(a) $D = 1.3$ mm, (b) $D = 1.0$ mm and (c) $D = 0.7$ mm

Fig. 14. Time variation of the bubble shapes under deceleration of $Bo = 9.82$ ($a = -50 \text{ m/s}^2$) from $Ca_0 = 0.122$ in a 1.3 mm tube for FC-40/air experiment.

Fig. 15. Schematic diagram of velocity profiles.
(a) Steady and (b) decelerated conditions.

Fig. 16. Predictions of liquid film thickness under steady condition by Eqs. (8) and (9).

Fig. 17. RHS of Eq. (14) against deceleration Bond number ($\rho a D^2 / \sigma$).

(a) Water

(b) Ethanol

(c) FC-40

Fig. 18. Predicted initial liquid film thickness (δ_0/D) against capillary number (Ca),
(a) Water, (b) Ethanol and (c) FC-40.

Fig. 19. Comparison between prediction by Eq. (17) and experimental data.