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Yuki Yoshinaga

The University of Tokyo, Japan, m136727@h.k.u-tokyo.ac.jp

Hao Peng

Beijing University of Civil Engineering and Architecture, China, pengchuanhao@gmail.com

Chaobin Dang

The University of Tokyo, Japan, dangcb@k.u-tokyo.ac.jp

Eiji Hihara

The University of Tokyo, Japan, hihara@k.u-tokyo.ac.jp

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Experimental Study on Liquid Film Thickness of Annular Flow in Microchannels

Yuki YOSHINAGA¹, Hao PENG², Chaobin DANG^{1*}, Eiji HIHARA¹

¹Department of Human and Engineered Environment, Graduate School of Frontier Sciences,
The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa-shi, Chiba 277-8563, Japan,
(TEL/FAX: +81-47-136-4647, dangcb@k.u-tokyo.ac.jp)

²Department of Energy and Power Engineering, Beijing University of Civil Engineering and Architecture,
Beijing, 100044, China

ABSTRACT

Many studies were carried out to investigate the flow and heat transfer characteristics of two-phase flow in microchannels because of its advantage in improving heat exchange performance, it has been well revealed that liquid film thickness and flow pattern play important roles in determining the heat transfer characteristics. However, these data is still limited to understanding properties of two-phase flow in microchannels because both the effect of tube size, geometry and physical property of working fluids have be taken into account.

In this study, visual observation of flow pattern by using a high-speed camera and direct measurement of liquid film thickness by using a laser displacement meter for annular flow inside microchannels with inner diameter of 0.5 mm, 1 mm and 2 mm were conducted. 5 fluids with different surface tension and viscosity (water, ethanol, FC72, KF-96L-0.65cs, KF-96L-2cs) were selected to investigate the effect of physical properties on the flow pattern and liquid film thickness. Experimental results were compared with numerical simulation model results to provide better understanding of two phase flow and heat transfer characteristics at various tube scales and working fluid physical properties.

1. INTRODUCTION

To understand mechanism of two phase flow in microchannels is important for developing microscale heat transfer, microreactor, microscale process units, biotechnology systems as well as in potential space applications, and microscale electric device. However, two phase flow in microchannels has a lot of factors which decides its behavior, so it's making us hard to get a universalistic science. A number of studies regarding two phase flow tried to figure out effect of each factors to provide better understandings, but unfortunately, especially in micro scale, the data is still limited.

Flow pattern is one of the factors affecting the two phase heat transfer performance. Especially, in micro scale, it influenced by various parameters, channel size, phase superficial velocities, liquid phase surface tension, and so on. Shao *et al.* (2009) reviewed well more than 20 studies on flow patterns of two phase flow in microchannels. In their review, comparing these flow pattern maps from several perspectives, they concluded flow pattern map based on j_G , j_L coordinate represented best transitions between the different patterns. And also they mentioned flow pattern maps based on dimensionless number sometimes lead to large discrepancies because changes in the dimensionless numbers because of changes in some parameters affect all the transition lines contrary to what is found experimentally. On the other hand, it wasn't possible to conclude on the effect of liquid viscosity to flow pattern due to the still limited amount of data available.

Yoshinaga *et al.* (2014) observed two phase flow pattern in microchannels by using high speed camera. They used 5 kinds of fluids(water, ethanol, FC72, 2 different kinds of silicon oil, KF-96L-0.65cs and KF-96L-2cs) to investigate the effect of liquid phase physical properties on the flow pattern. And they concluded that liquid viscosity has relatively smaller effect on its flow pattern than other parameters, channel size and liquid phase surface tension. And they also measured bubble velocity, and liquid film thickness of slug flow by using laser focus displacement meter which is the method suggested by Han and Shikazono (2009). As a result of comparison with correlations in previous studies, Gregory and Scott's (1969) correlation and Aussillous and Quere's (2000) correlation showed good

agreement with their experimental data.

Generally speaking, liquid phase surface tension plays dominant rule in microscale tubes compared to those in miniscale or larger scale tubes. When refrigerants are used as working fluids, which has a low surface tension, annular flow become the prevailing flow patterns for both the flow boiling and condensation process. Several studies on liquid film thickness of annular flow have been carried out. Kanno *et al.* (2010) conducted experimental measurement of liquid film thickness and flow pattern observation of annular flow in circular microchannels of 0.3 ~ 0.5 mm at mass flux of 100 ~ 500 kg/m²s. By comparing their experimental data of dimensionless liquid film thickness with the annular film model proposed by Revellin *et al.* (2008), they conclude that prediction mode overestimates the experimental results at smaller vapor quality, which was attributed to the interface instabilities caused by the ripples especially in low vapor quality.

In present study, 5 fluids with different surface tension and viscosity (water, ethanol, FC72, KF-96L-0.65cs, KF-96L-2cs) were selected to investigate the effect of physical properties on liquid film thickness of annular flow in microchannels. Experimental results were compared with numerical simulation model to provide better understanding of two phase flow and heat transfer characteristics at a various tube scale and working fluid physical properties.

2. Experimental setup and procedure

In present study, 5 fluids with different surface tension and viscosity (water, ethanol, FC72, KF-96L-0.65cs, KF-96L-2cs) were selected to investigate the effect of liquid physical properties on flow pattern, bubble velocity and liquid film thickness in microchannels. The properties of working fluids are listed in Table 1.

Table 1: Properties of the working fluids at 25°C

Fluid	Density ρ [kg/m ³]	Viscosity μ [μ Pa s]	Surface tension σ [mN/m]
Water	997	889	70
Ethanol	785	1088	22.3
FC72	1680	672	12
KF-96L-0.65cs	740	494	15.9
KF-96L-2cs	873	1746	17.7

Circular Pylex glass tubes with inner diameters of 0.5, 1.0 and 2.0 mm were used as test channels. The length of all tubes is 300 mm. Figure 1 shows a schematic diagram of the experimental setup. The liquid phase is injected into the test channel at preassigned flow rate by syringe pumps (Harvard Apparatus, accuracy within 0.35% and reproducibility within 0.05%). An air compressor is used to supply the air and the flow rate was measured by a flow meter (Kofloc, accuracy $\pm 1\%$ of full scale). The liquid phase and gas phase are mixed at a T-junction and then introduced into the glass tube. Flow regime was observed with high speed camera (Keyence, VW-600C). Frame rate and shutter speed were 35000 fps and 900 kHz, respectively, and all pictures were taken in 256 \times 128 pixel size. Liquid film thickness was measured with laser focus displacement meter (LFDM) (Keyence, LT9010). The resolution of LFDM is 0.01 μ m and response time is 640 μ s, with a laser spot diameter of 2 μ m, and focal point distance of about 5 mm. The LFDM converts the data of liquid film thickness to ± 10 V signal, and transfer it to a PC through a data logger.

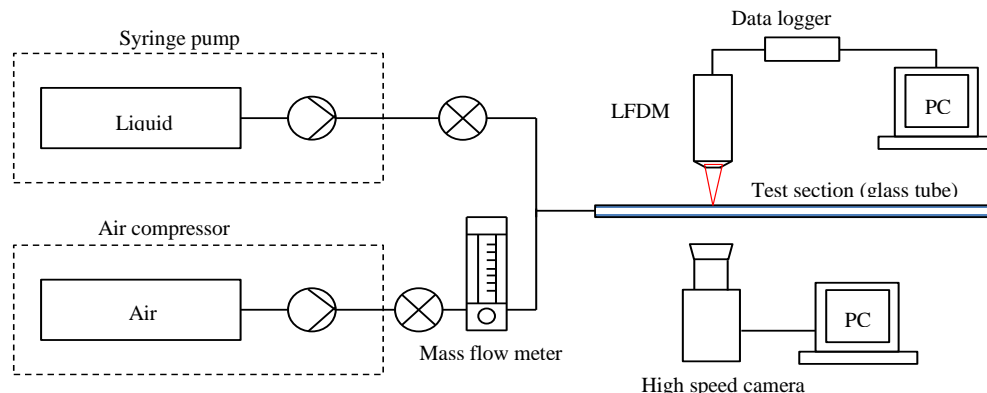


Figure 1: Schematic diagram of experimental apparatus

3. Results and Discussion

3.1 Flow regime and Dimensionless liquid film thickness

3.1.1 Influence of tube diameter

Figure 2 shows a typical example of flow regime and measured signal by LFDM at different tube diameters and vapor qualities. Experiments were conducted for air-water at annular flow condition with mass flux of $75 \text{ kg/m}^2\text{s}$. As shown in both the flow pattern observation and measured LFDM signal, even for 0.5 mm tube at a low vapor quality of 0.2, roll wave together with higher frequency turbulence occurs at the vapor-liquid interface. With the increase in the tube diameter, the frequency of both the roll wave and the turbulence increases, implying enhanced interfacial disturbance. While the amplitude of the roll wave and turbulence decrease with the increase in vapor quality. Figure 3 shows the result of dimensionless mean liquid film thickness which calculated by averaging each signal for 10 seconds, the dimensionless mean liquid film thickness decreases as tube diameter and vapor quality increases.

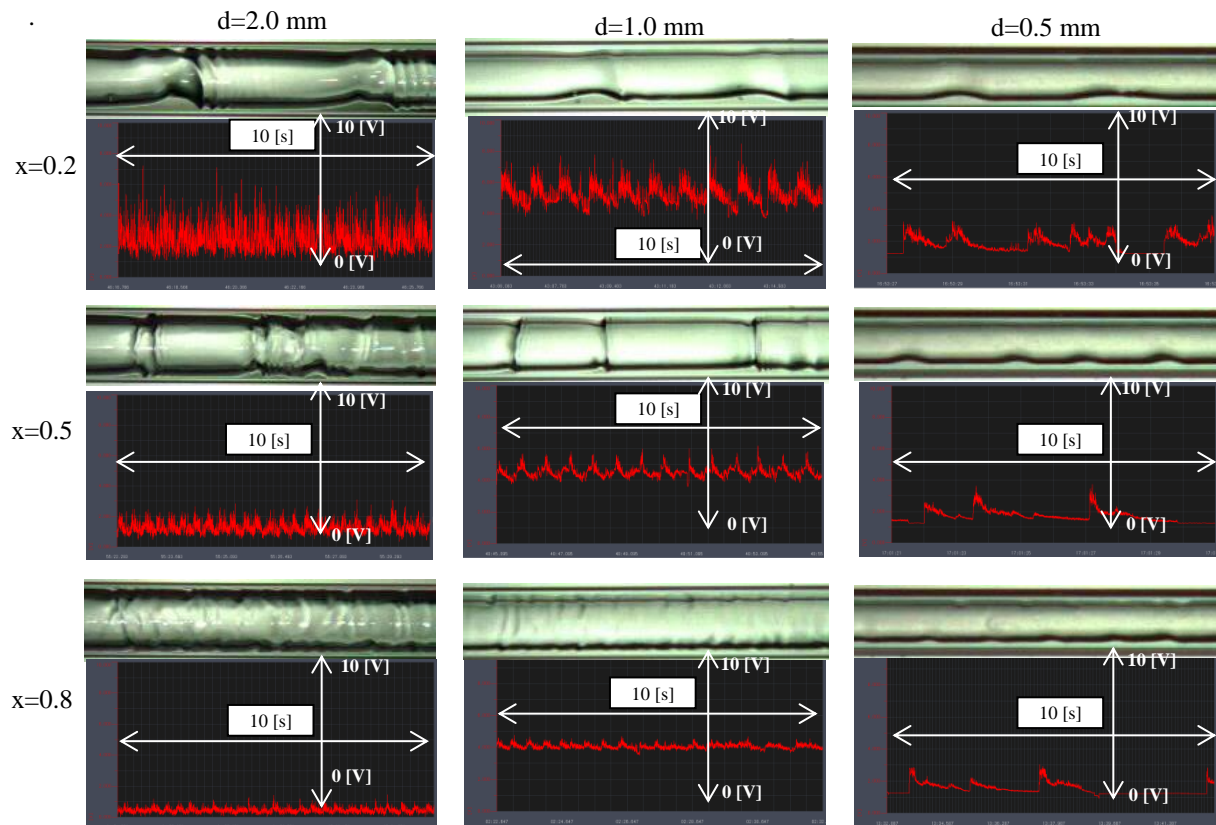


Figure 2: Air-water annular flow, $G=75 \text{ [kg/m}^2\text{s]}$

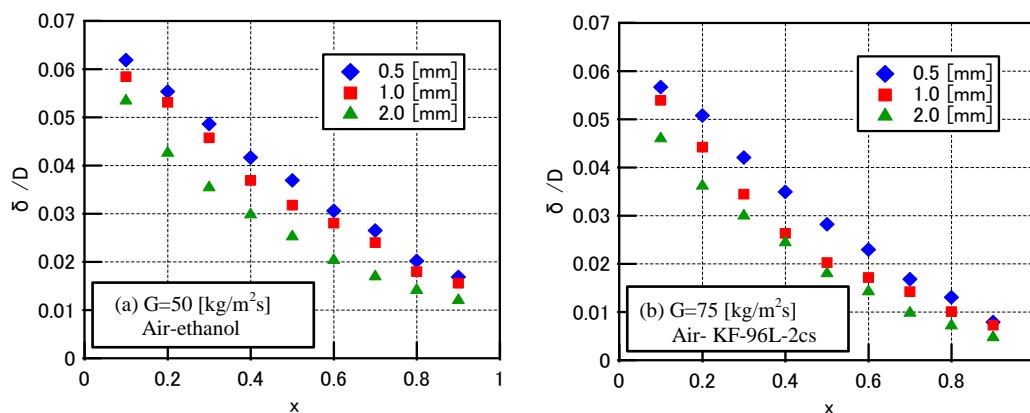


Figure 3: Dimensionless mean liquid film thickness

3.1.2 Influence of mass flux

Figure 4 shows the results of flow regime and measured signal by LFDM at different mass fluxes and vapor qualities. It is seen that the amplitude of the roll wave and turbulence increases slightly with the decreases in liquid mass flux. However, the vapor quality has significant effect of the amplitude of the turbulence. Figure 5 shows results of dimensionless mean liquid film thickness for air-ethanol and air-KF-96L-2cs in annular flow regime. As shown in Figure 5, dimensionless liquid film thickness becomes thinner as mass flux increases. This trend is also similar to Kanno's (2010) experimental data.

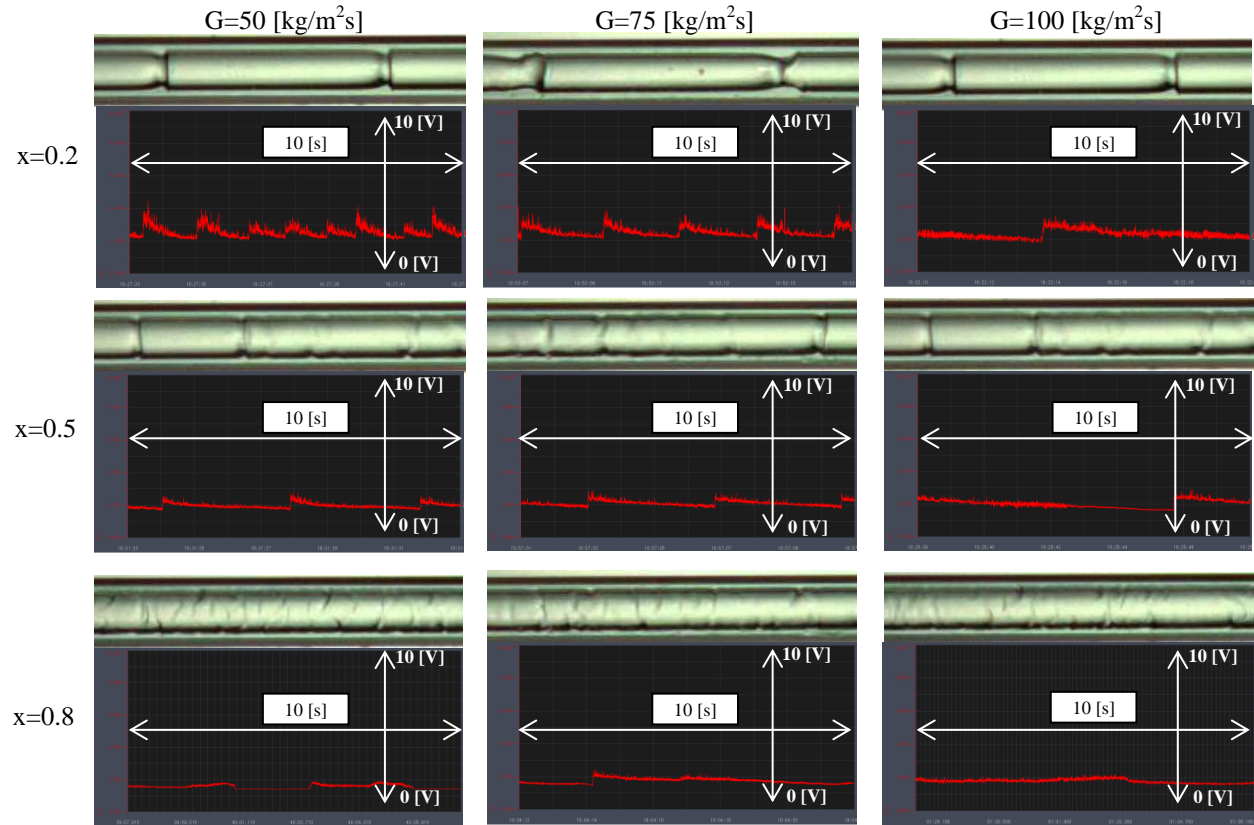


Figure 4: Air-ethanol annular flow, $d = 0.5$ [mm]

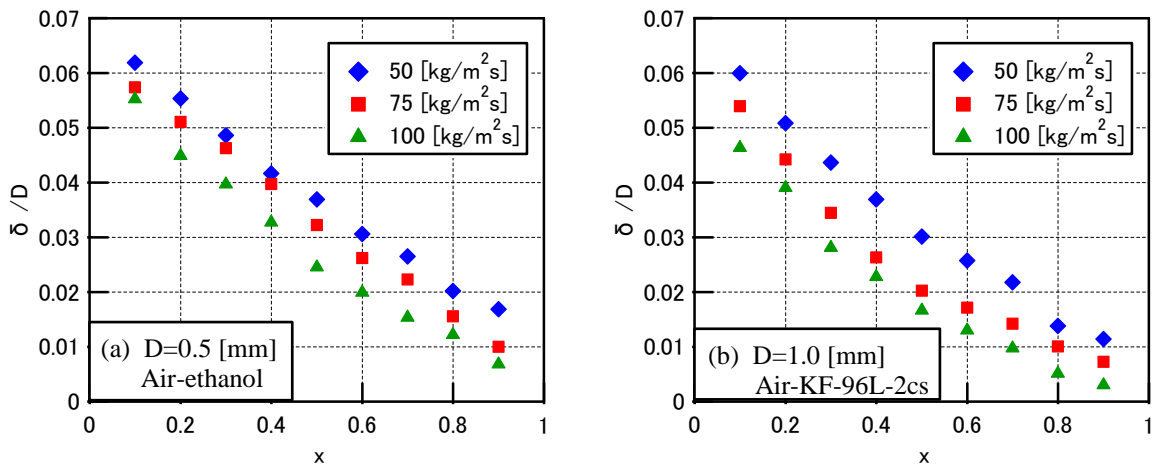


Figure 5: Dimensionless mean liquid film thickness

3.1.3 Influence of physical property μ , σ :

Figure 6 shows results of flow regime and measured signal by LFDM to see influence of physical property. Experimental condition is air-water, fc72, KF-96L-2cs, and mass flux $G=100$ [$\text{kg}/\text{m}^2\text{s}$], tube diameter $D=2.0$ [mm]. And figure 7 shows results of dimensionless mean liquid film thickness for air-5 kinds of liquids. From figure 6 and figure 7, it is considered that the amplitude of turbulence become larger as viscosity increases. And as surface tension decreases, flow regime becomes easy to be jumbled and peaks (ripples) become smaller. And also it can be considered dimensionless liquid film thickness is influenced by combination of viscosity and surface tension. So it is considered dimensionless liquid film thickness can't be determined uniquely by physical property of liquid phase.

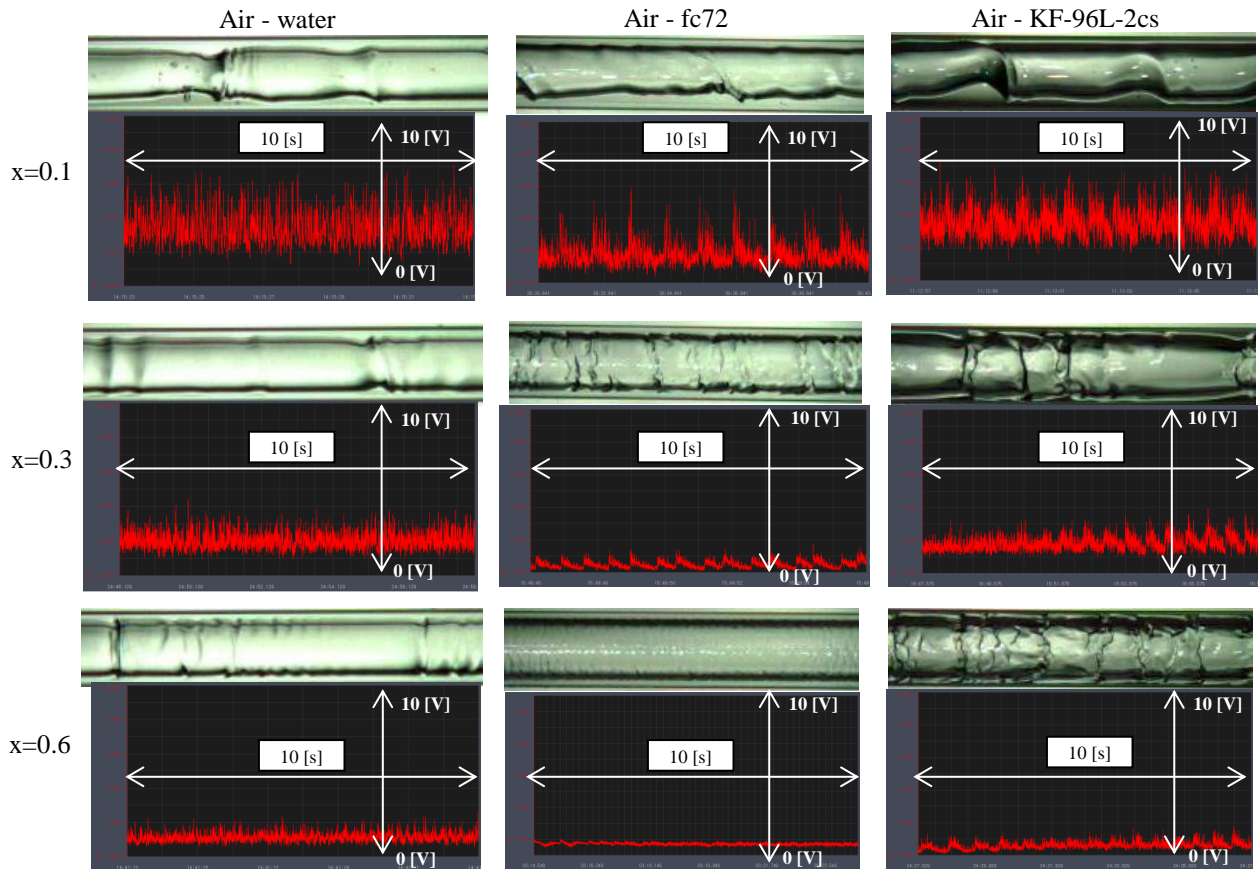


Figure 6: Air-different fluid annular flow, $G=100$ [$\text{kg}/\text{m}^2\text{s}$], $D=2.0$ [mm]

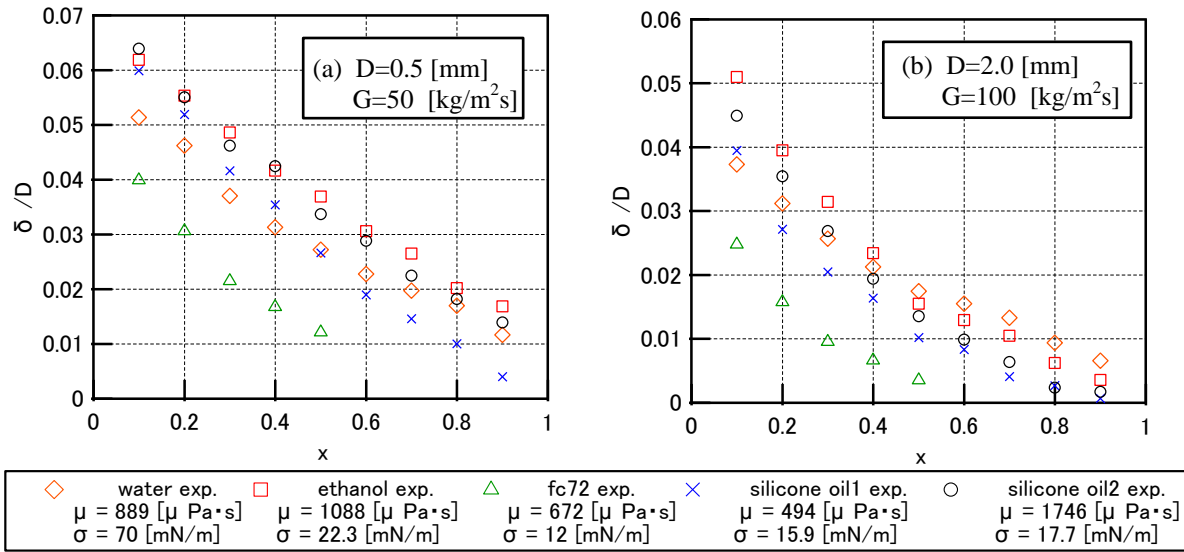


Figure 7: Dimensionless mean liquid film thickness

3.2 Model for prediction of liquid film thickness

Figure 8 shows a laminar liquid flow model to determine the liquid film thickness δ from interfacial shear stress τ .

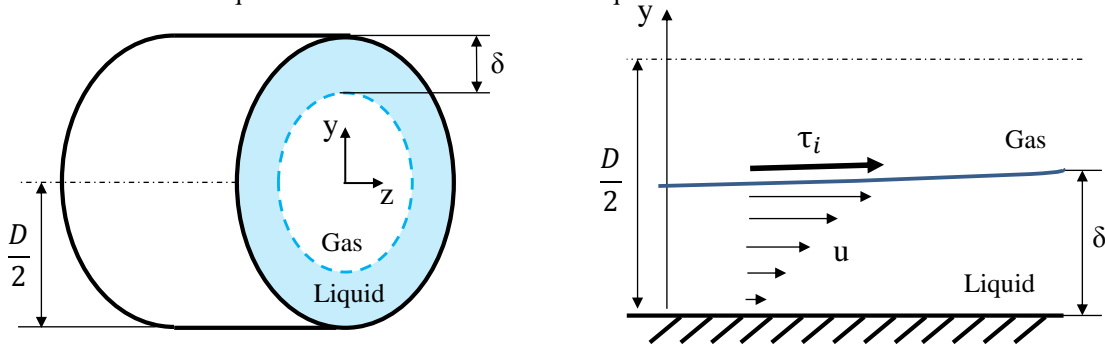


Figure 8: Laminar liquid flow model

The relationship of shear stress τ and liquid film velocity u is

$$\tau = \mu_l \frac{du}{dy} \quad (1)$$

As liquid film velocity is linearly proportional along the y direction for laminar flow, shear stress at liquid-vapor interface is

$$\tau_i = \mu_l \frac{u_i}{\delta} \quad (2)$$

Then, the liquid film velocity u could be derived:

$$u = \frac{u_i}{\delta} y = \frac{\tau_i}{\mu_l} y \quad (3)$$

The mass flow rate of liquid film is

$$m_l = GA(1 - x) = \int_0^\delta \rho_l u 2\pi \left(\frac{D}{2} - y\right) dy \quad (4)$$

Then, substituting equation (3) into equation (4),

$$m_l = \frac{2\pi\rho_l\tau_i}{\mu_l} \int_0^\delta \left(\frac{D}{2} - y\right) y dy \approx \frac{\pi d\rho_l\tau_i}{2\mu_l} \delta^2 \quad (5)$$

Then, the liquid film thickness is,

$$\delta^2 = \frac{G(1-x)d\mu_l}{2\rho_l\tau_i} \quad (6)$$

shear stress at liquid-vapor interface:

$$\tau_i = \left(\frac{dp}{dz}\right)_g \Phi_g^2 \frac{D}{4} \quad (7)$$

where,

$$\left(\frac{dp}{dz}\right)_g = f_g \frac{2\rho_g u_g^2}{D} \quad (8)$$

Then, substituting equation (8) into equation (7), shear stress at liquid-vapor interface is,

$$\tau_i = f_g \frac{2\rho_g u_g^2}{D} \Phi_g^2 \frac{D}{4} = \frac{G^2 x^2}{2\rho_g} f_g \Phi_g^2 \quad (9)$$

where, f_g and Φ_g^2 are well known friction factor and two-phase friction multiplier (Lockhart and Martinelli 1949) respectively as shown in equation (10) and equation (11).

$$f_g = \frac{16}{Re_g} \quad (Re_g = \frac{2\rho_g u_g (\frac{D}{2} - \delta)}{\mu_g} < 2300) \quad , \quad f_g = 0.078 Re_g^{-0.25} \quad (Re_g \geq 2300) \quad (10)$$

$$\Phi_g^2 = X^2 + CX + 1 \quad (11)$$

$$X^2 = \frac{\left(\frac{dp}{dz}\right)_l}{\left(\frac{dp}{dz}\right)_g} = \frac{f_l \frac{\rho_l u_l^2}{2d}}{f_g \frac{\rho_g u_g^2}{2d}} = \frac{f_l \rho_v (1-x)^2}{f_v \rho_l x^2} \quad (12)$$

Here, f_l is friction factor for liquid phase,

$$f_l = \frac{16}{Re_l} \quad (Re_l = \frac{2\rho_l u_l \delta}{\mu_l} < 2300) \quad , \quad f_l = 0.078 Re_l^{-0.25} \quad (Re_l \geq 2300) \quad (13)$$

where, X (Lockhart and Martinelli 1949) and C (Chisholm 1967) are parameters to calculate the two-phase frictional multiplier. C is changed in accordance with the flow condition as shown in equation (14).

Table 2: Chisholm's parameter

Liquid phase	Gas phase	C
Turbulent	Turbulent	20
Laminar	Turbulent	12
Turbulent	Laminar	10
Laminar	Laminar	5

Mishima and Hibiki (1996) found Chisholm's experimental parameter C is affected by tube diameter in microchannels with their experimental results (diameter is 1.05~4.08mm, vertical circular tube). And they modified C for microchannel as shown in equation (14), where D is tube diameter in 'mm'.

$$C = 21(1 - e^{-0.333D}) \quad (14)$$

3.3 Comparison with experimental data and model

Figure 9 shows comparison of Revellin’s model and experimental data, experiment condition is air-water two phase flow in 0.5 mm tube at mass flux of 100 kg/m²s. As shown in Figure 9, there is a non-continuous change in mean liquid film thickness. This is because of change of flow regime laminar to turbulent where Reynolds number in gas phase become larger than 2300. And there is a large difference between experimental result and model prediction especially in low vapor quality. This trend is similar to Kanno’s result (2010). In Revellin’s model, shear stress for each phase is determined by using the conventional relation for single phase flow. So it is not considered that shear stress where vapor and liquid as a two phase flow. Thus, the difference between experimental result and model prediction becomes larger in low quality region which can be observed large ripples frequently. These ripples make the model incorrect to express the shear stress where liquid and gas interface.

Figure 10 is a comparison of predicted dimensionless liquid film thickness at different C value. And condition of experimental data is same in Figure 9. In this study, Reynolds number in liquid phase is under 2300 in all experimental data, and about Reynolds number in gas phase, almost of them are smaller than 2300. So, as shown in Table 2, C should take number ‘5’ according to Chisholm’s study (1967). And also, by using equation (14), C can be calculated as 3.22 in this experimental condition. However, the prediction showed good agreement with the experimental data when C=20 which for both phase are turbulent flow. Thus, it is considered Chisholm’s correlation predicts shear stress where liquid-vapor interface lower than real situation in microchannel.

Figure 11 is a typical example of comparison with experimental results and model prediction using C=20. As shown in Figure 11, water, ethanol, and KF-96L-2cs showed good agreement with the experimental data. However,

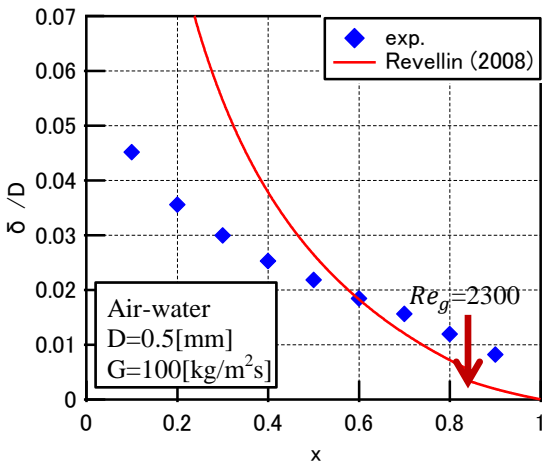


Figure 9: Comparison with Revellin’s model (2008)

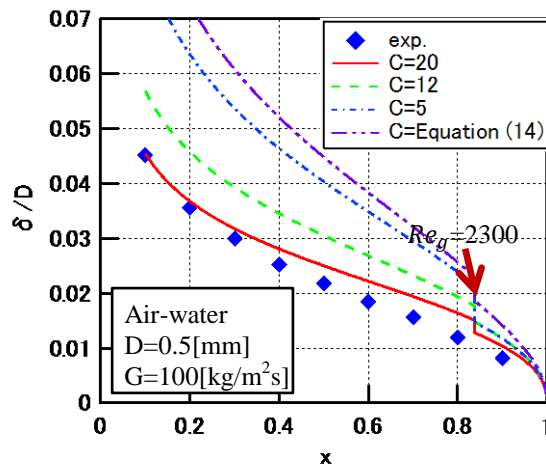


Figure 10: Comparison of prediction with different C

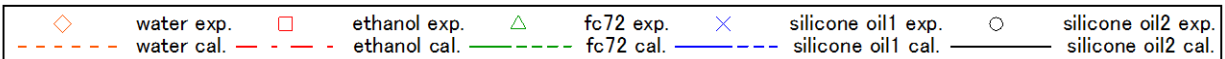
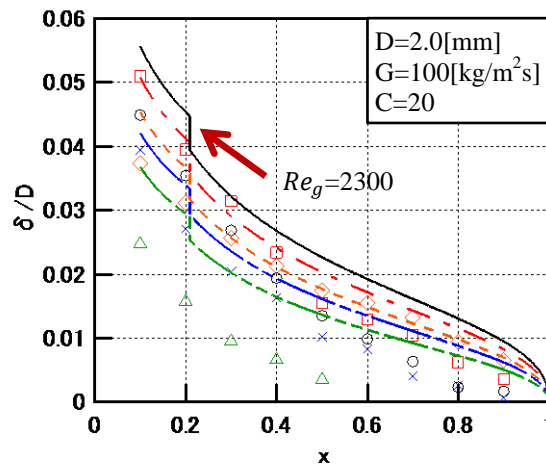
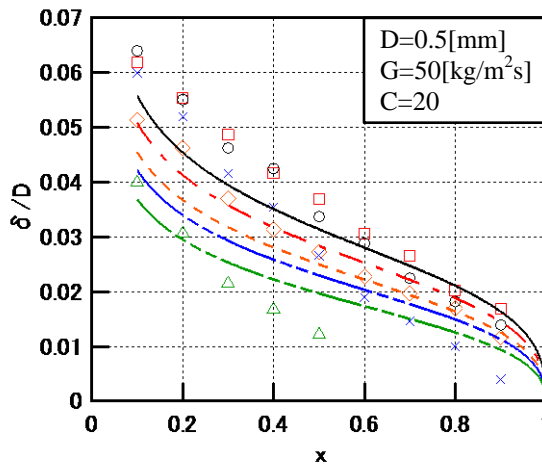


Figure 11: Comparison with prediction model (C=20) and experimental results

KF-96L-0.65cs and FC72 has a relatively large difference between the prediction and the data. These two liquids have the lowest viscosity and surface tension in 5 kinds of liquids in this study. And also, only in air-FC72 experiment, it can be seen there is a phenomenon which evaporate FC72 into air phase. So in high quality, liquid film was not observed.

And as tube diameter D and mass flux G increases, the difference between experimental data and model prediction becomes larger and the model predicts larger dimensionless liquid film thickness than experimental data. This means as tube diameter D and mass flux G increases, proper Chisolm's parameter C increases.

4. CONCLUSIONS

In present study, 5 fluids with different surface tension and viscosity (water, ethanol, FC72, KF-96L-0.65cs, KF-96L-2cs) were selected to investigate the effect of liquid physical properties on liquid film thickness of annular flow in microchannels. And experimental results were compared with numerical simulation model.

Liquid film thickness was measured by using laser focus displacement meter. Dimensionless liquid film thickness becomes thinner as mass flux G and tube diameter increases D . So it can be considered these trends are uniform even in lower mass flux condition.

As a result of comparison with simulation model, Revellin's model (2008) showed relatively large difference in low vapor quality as same as Kanno's result (2010). The model proposed in this study showed good agreement with experiment data when Chisolm's parameter $C = 20$. But in case of liquid which has low viscosity and surface tension, the difference between the prediction and experimental data becomes relatively large.

And it is considered Chisolm's correlation predicts shear stress where liquid-vapor interface lower than real situation in microchannel. And as tube diameter D and mass flux G increases, proper Chisolm's parameter C increases.

NOMENCLATURE

C	Chisolm's parameter	(-)
D	Tube inner diameter	(mm)
f	Friction factor	(-)
G	Mass flux	(kg/m ² s)
m	Mass flow rate	(kg/s)
p	Pressure	(N/m ²)
Re	Reynolds number	(-)
u	Velocity	(m/s)
X	Lockhart and Martinelli's parameter	(-)
x	Vapor quality	(-)

Greek symbol

δ	Liquid film thickness	(mm)
μ	Viscosity	(μ Pa s)
ρ	Density	(kg/m ³)
σ	Surface tension	(N/m)
τ	Shear stress	(N/m ²)
Φ	Two-phase multiplier	(-)

Subscript

cal.	Calculation
exp.	Experiment
G,g	Gas phase
i	Interface
L,l	Liquid phase

REFERENCES

- Aussillous, P., Quere, D., 2000, Quick deposition of a fluid on the wall of a tube, *Physics of Fluids*, American Institute of Physics, Vol. 12, No. 10, pp. 2367-2371.
- Chisholm, D., 1967, A theoretical basis for the Lockhart-Martinelli correlation for two-phase flow, *Int. J. Heat Mass Transfer*, Pergamon Press Ltd, vol. 10: p. 1767-1778.
- Gregory, G.A., Scott, D.S., 1969, Correlation of liquid slug velocity and frequency in horizontal cocurrent gas-liquid slug flow, *J. American Institute of Chemical Engineers*, Wiley Online Library, Vol. 15, No. 6, pp. 933-935.
- Han, Y., Shikazono, N., 2009, Measurement of the liquid film thickness in micro tube slug flow, *Int. J. Heat and Fluid Flow*, Elsevier Science Ltd, Vol. 30, pp. 842-853.
- Kanno, H., Han, Y., Saito, Y., Shikazono, N., 2010, Measurement of liquid film thickness in micro tube annular flow, *Proceedings of the 14th Int. Heat Transfer Conference*, ASME: p. 1-8.
- Lockhart, R.W., Martinelli, R.C., 1949, Proposed correlation of data for isothermal two-phase, two component flow in pipes, *Chemical Engineering Progress*, Trans. American Institute of Chemical Engineers, vol. 45, no. 1: p. 39-48.
- Mishima, K., Hibiki, K., 1996, Some characteristics of air-water two-phase flow in small diameter vertical tubes, *Int. J. Multiphase Flow*, Elsevier Science Ltd, vol. 22: p. 703-712.
- Shao, N., Gavriilidis, A., Angeli, P., 2009, Flow regimes for adiabatic gas-liquid flow in microchannels. *Chemical Engineer Science*, UCL Discovery, Vol. 64, pp. 2749-2761.
- Revellin, R., Haberschill, P., Bonjour, J., Thome, J.R., 2008, Conditions of liquid film dryout during saturated flow boiling in microchannels, *Chemical Engineering Science*, Elsevier Ltd, vol. 63: p. 5795-5801.
- Yoshinaga, Y., Dang, C., Hihara, E., 2014, Experimental study on two phase flow pattern and liquid film thickness in microchannels, *Proceedings of the 7th Asian Conference on Refrigeration and Air Conditioning*, C2, 449.

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