低キャピラリー数領域におけるスラグ流の流動特性に関する研究

Investigation of slug flow characteristics in low capillary number region

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Two phase flow in micro channel has been of research interest recently due to its high heat and mass transfer rate, and in this study, experimental and numerical investigation is performed on slug flow characteristics in mini channels, the influence of wettability of the inner wall on slug flow is studied as well. The result of liquid film thickness agrees well with that of numerical simulation and existing correlations. And the influence of wettability of channel surface is found to be negligible on liquid film thickness, however, it's observed that the bubble behavior is influenced by wettability when bubble velocity is low. Numerical simulation of the expansion a vapor bubble in a diverging tube during flow boiling is conducted, bubble profile, bubble growth rate and wall heat flux distribution are investigated to provide better understanding on flow boiling in diverging tubes.

Key words: Slug Flow, Mini Channel, Liquid Film, Numerical Simulation, Flow Boiling

1 Introduction

With the advancement in microfabrication techniques, micro-structured device such as mini channel exchanger and microfluidics has gained importance in a range of industrial application. To better design these micro devices, it's significant to understand two phase flow characteristics in micro channels. In most cases, slug flow is frequently encountered due to the dominant surface tension in mini channels. And the slug flow characteristics under adiabatic condition is experimentally investigated in this research, flow pattern, liquid film thickness and influence of channel surface properties are studied in detail, and the result agrees well with the existing research. In addition, it's observed that slug flow in the diverging channel shows very good pressure drop characteristics and stability during flow boiling, however, the research on diverging channels is limiting, therefore, numerical simulation is conducted for slug flow a diverging tube during flow boiling, bubble profile, bubble growth rate and wall heat flux distribution are investigated to provide better understanding on flow boiling in diverging tubes.

2 Experimental study

2.1 Experimental setup

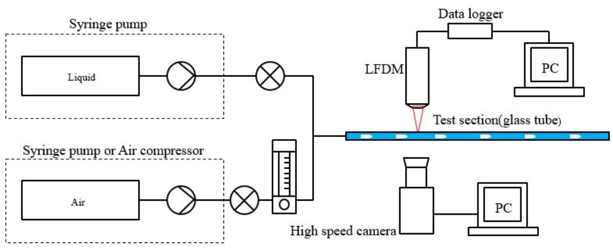
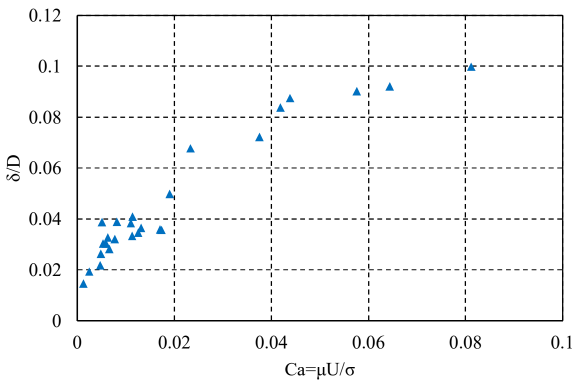


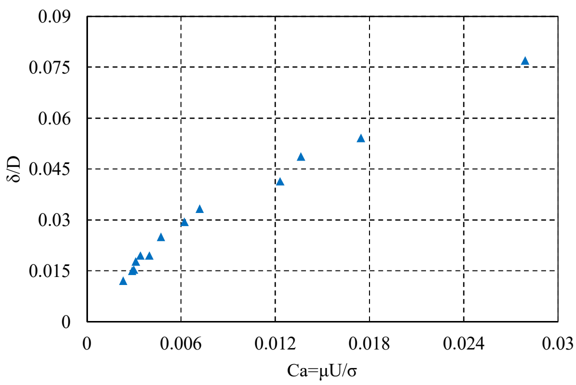
Fig. 1 Schematic diagram of experimental apparatus [1]

The schematic diagram of the experimental apparatus is shown as Fig. 1. Water and air are injected by syringe pumps (Harvard Apparatus, accuracy within 0.35%, reproducibility within 0.05%), then they are mixed in the T-junction and introduced into the test section (circular Pyrex tube with diameters of 0.76mm and 1mm). The flow pattern is recorded by high speed camera (Keyence, VW-600C), and the liquid film thickness is measured by laser focus displacement meter (LFDM) (Keyence, LT9010). The resolution of LFDM is 0.01μm, the response time is 640μs, the diameter of the laser spot is 2μm, and the focal length of the lens in the LFDM is about 5mm. Measured liquid film thickness is transformed to DC voltage signal in the range of ±10 V, and the data is transferred to a PC through the data logger.

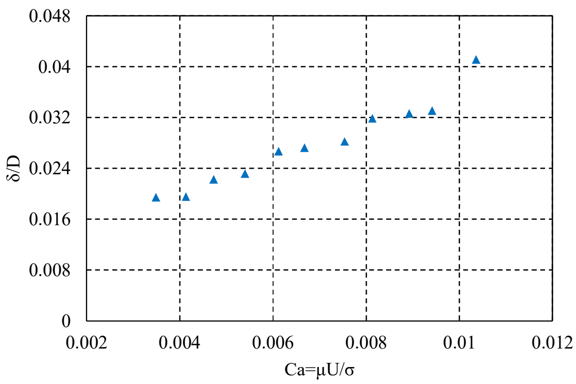
2.2 Liquid film thickness



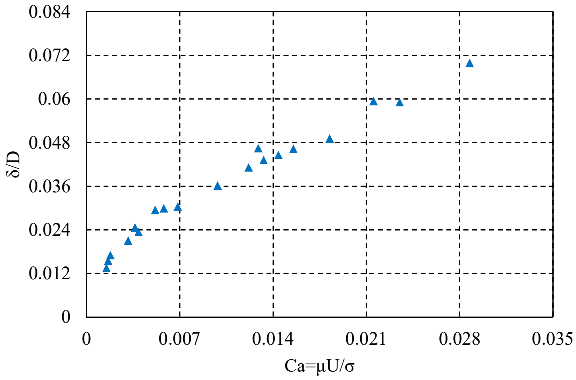
(a) D = 0.24 mm



(b) D = 0.5 mm



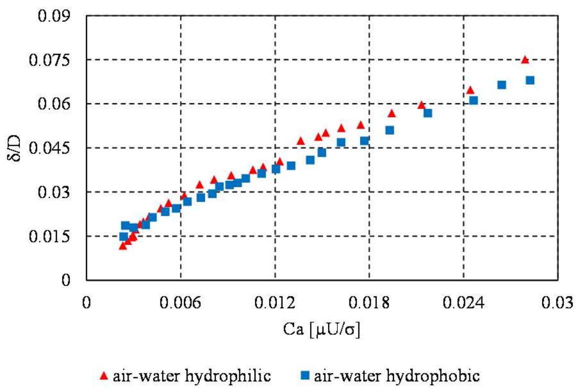
(c) D = 0.76 mm



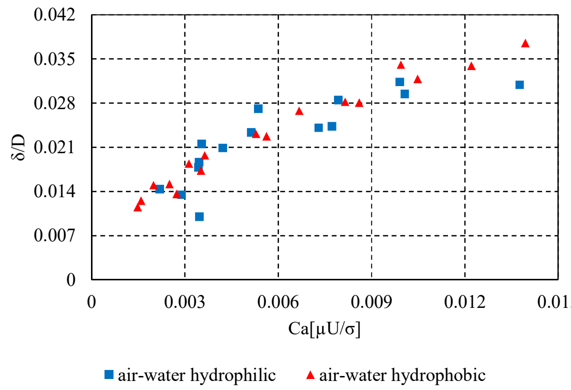
(d) D = 1 mm

Fig. 2 Measured liquid film thickness in tubes of different diameters

The liquid film thickness increases rapidly with capillary number at low capillary number, but the trend slows down as the capillary number increases, which agrees well with existing correlations. Moreover, the effect of wettability is investigated. The results for tubes of different wettability and diameters are shown in Figs. 3 (a) and (b), respectively. The liquid film thickness in hydrophilic tube is found to be slightly thicker than that in hydrophobic tube (Fig. 3 (a), inner D = 0.76mm). However, in the tube diameter of 1mm (Fig. 3 (b)), the liquid film thickness is undistinguishable in hydrophobic and hydrophilic tubes. And the small difference of results probably comes from the measurement uncertainty of bubble velocity, because it is very difficult to keep the bubble travelling at a constant velocity.



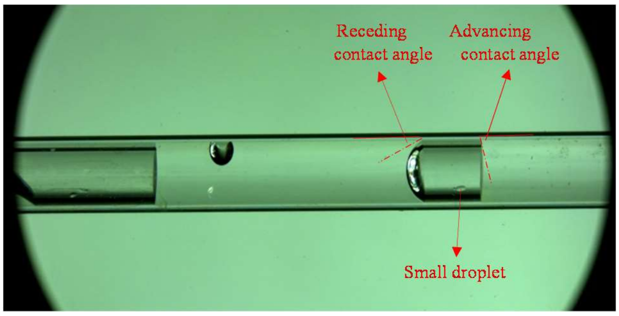
(a) D = 0.76 mm



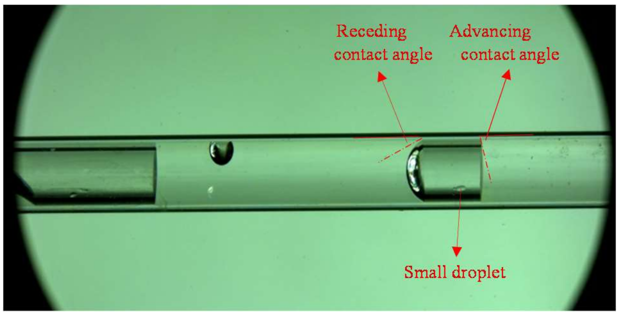
(b) D = 1 mm

Fig. 3 liquid film thickness of slug flow in hydrophilic and hydrophobic tubes

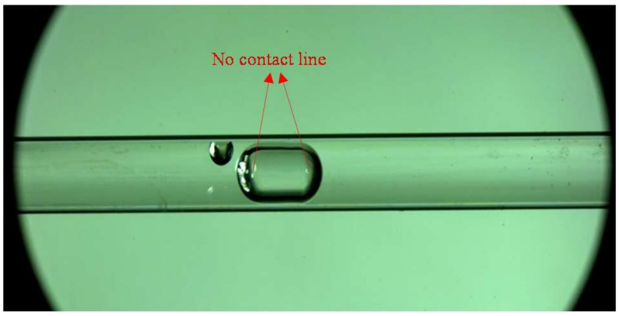
2.3 Visual observation



(a)



(b)



(c)

Fig. 4 Process of liquid film formation

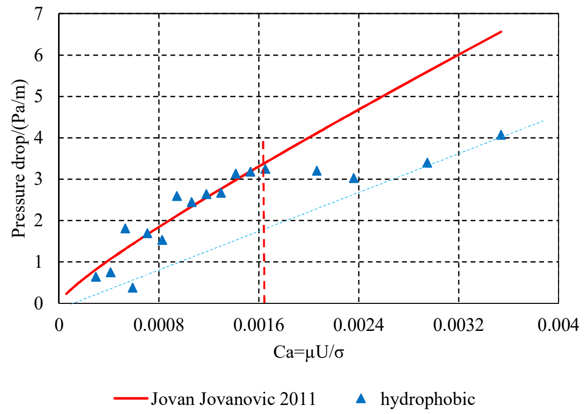
Visual observation is employed to investigate the influence of wettability at low capillary region (as circled in Fig. 4 (a) ~ (c)). As a result, when the capillary number is low, there is no liquid film around the bubble, and the bubble is directly in contact with the inner wall of the tube.

This conclusion is based on the following observation: 1) There is a small droplet on inner wall (Fig. 4 (a) and (b)), which indicates the liquid film does not exist. Because a droplet cannot lie on liquid film, otherwise they will merge together. 2) Contact lines are observed at the bubble head and tail (Fig. 4 (a) & (b)). And the contact line is the intersection of three phases (solid-liquid-gas), indicating there is no liquid film around the bubble. Because if liquid film exists, it will separate solid phase (inner surface of the tube) and vapor phase (air in the bubble), and in this case, only two-phase intersection exists (vapor-liquid interface and liquid-solid interface), which is contradictory with the observation. 3) Due to the existence of contact line, a dry bubble has sharp transition part in bubble head and tail (Fig. 4 (a) & (b)), but the bubble head and bubble tail becomes smooth and nearly spherical (Fig. 4 (c)) when it's lubricated by liquid film.

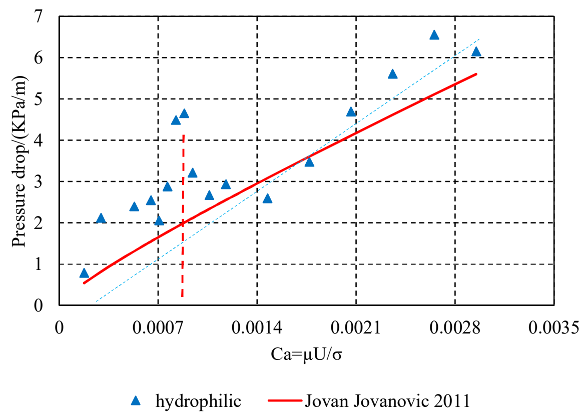
It's found that when the capillary number is lower than a critical value, liquid film does not exist. And the critical capillary number is influenced by the wettability of tubes. As a result, the critical capillary number for liquid film formation is about 1.24×10^{-3} and 8.68×10^{-5} for hydrophobic and hydrophilic tubes.

2.4 Pressure drop characteristics

Fig. 5 (a) to Fig. 5 (b) shows the pressure drop generally increases with the increase of capillary number, and the results for hydrophobic and hydrophilic tubes agree well with the prediction of Jovan Jovanovic's model. Nonetheless, it's necessary to notice that the pressure drop characteristics seem to be segmented to two parts, especially for the hydrophobic case (Fig. 5 (a)). The first part of the pressure drop, which is in the lower capillary number region, is higher than the extrapolated values from the second part, which is represented as the blue dashed line. And the transition capillary numbers are 0.0009 and 0.00165 for hydrophilic and hydrophobic tubes respectively. The result is in correspondence to the observed critical capillary number in visual observation of result of critical capillary number, especially for the hydrophobic case



(a)



(b)

Fig. 5 Pressure drop in tubes (D = 1 mm) of different wettability

3 Derivation of critical capillary number

For a bubble moving in a capillary tube, there exists a critical capillary number, below which, the liquid film does not exist. The interface profiles are obtained for inner region and outer meniscus, respectively. And the critical capillary number is the critical value for matching of two profiles to be possible, if the capillary number is higher than the critical capillary number, the curvature of the inner region is two large to match the curvature of the outer meniscus, which is in the order of $1/R$. As a result, the critical capillary number for a regular capillary tube is approximated as $Ca_{cr} \approx \theta_{eq}^3/120$.

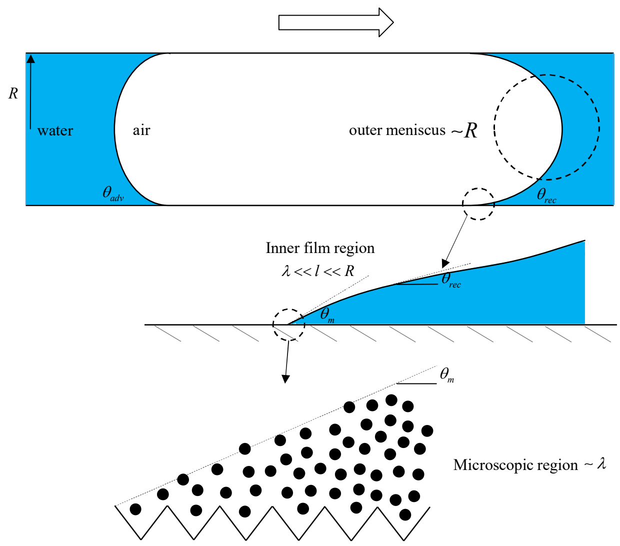


Fig. 6 Three length scales involved in a dry bubble moving in a tube.

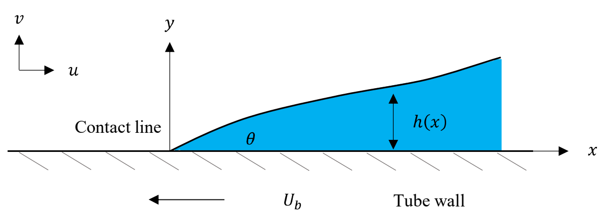


Fig. 7 Schematic view of the inner film region

$$h'''(x)=\frac{3Ca}{h^2(x)} \quad (1)$$

$$Ca_{cr} \approx \frac{\theta_{eq}^3}{189+\ln R} \quad (2)$$

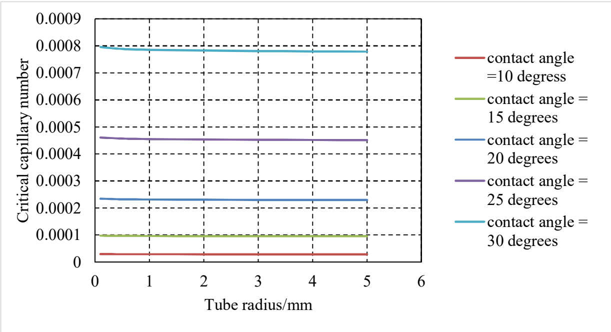


Fig. 8 Dependency of critical capillary number on tube radius and contact angle

And for ordinary micro channel, i.e. $0.1mm < R < 1mm$, it's reasonable to estimate the critical capillary number by equation 3-3:

$$Ca_{cr} \approx \frac{\theta_{eq}^3}{120} \quad (3)$$

The critical capillary number for a hydrophilic tube is in the order of 10^{-4}, which agrees with the experimental observation.

4 Numerical study

4.1 Growth of bubble

Numerical simulation is implemented for a water vapor bubble expansion in diverging tube during flow boiling (wall superheat=1k). Fig. 9 shows the geometrical configuration of the diverging tube, which is axisymmetric about its axis, with inlet diameter of 0.3mm, outlet diameter of 0.7mm, and length is 10mm

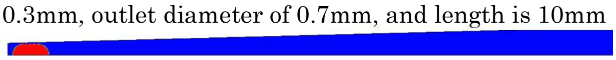


Fig. 9 Computational domain

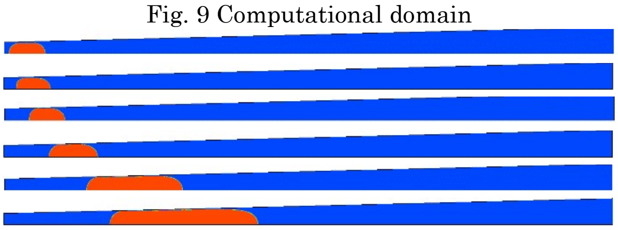


Fig. 10 Growth of bubble during flow boiling

Fig. 10 demonstrates the bubble expansion process, it's observed that the bubble is expanding in an increasing rate. It can be explained by the elongation of liquid film region, which results in enhanced mass transfer (evaporation).

4.2 Characteristics of bubble transport

Fig. 11 shows the bubble is accelerating due to elongated liquid film region and enhanced evaporation, and evaporation is dominant so that the bubble does not slow down due to increasing tube diameter.

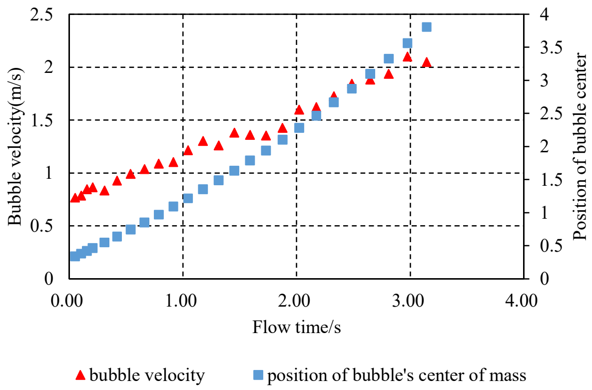


Fig. 11 Evolution of bubble velocity and position

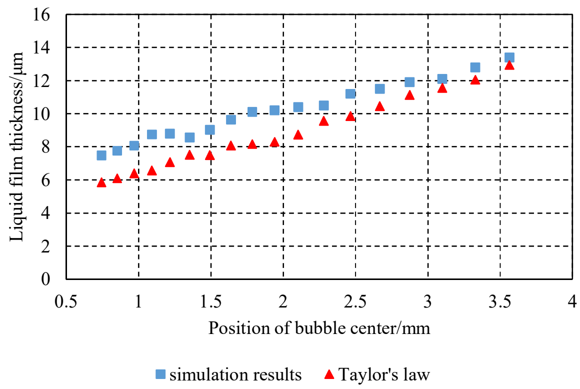


Fig. 12 Liquid film thickness as a function of bubble position

4.3 Heat transfer characteristics

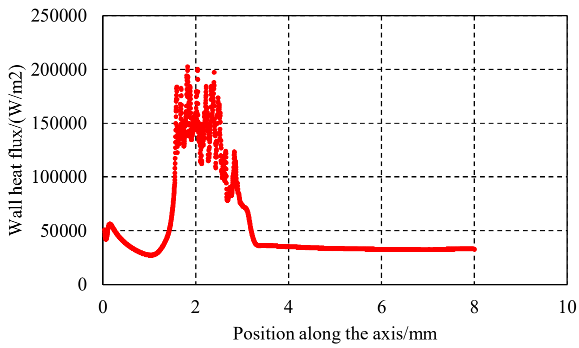


Fig. 13 Typical wall heat flux distribution.

Fig. 4.13 is a typical diagram of surface heat flux distribution along the wall, and the wall heat flux in the film region is much higher (nearly 4 times of that in liquid slug) than in the liquid slug.

5. Conclusions

The critical capillary number for liquid film formation is about 1.24×10^{-3} and 2.48×10^{-4} for hydrophobic (static contact angle = 109°) and hydrophilic tubes (static contact angle = 109°), respectively.

Reference:

[1] J. Xu, C. Dang, E. Hihara, Influence of wettability on slug flow in micro channel, Proceedings of the 9th Asian Conference on Refrigeration and Air-conditioning, 2018