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An Evaluation of Viscosity Models for the Prediction of the Two-phase Pressure Drop in Two-phase Flow through a Circular Micro-channel

Sira Saisorn[1, 2]
and Somchai Wongwises[2, 3]

[1] Department of Mechanical Engineering, King Mongkut's Institute of Technology Ladkrabang Chumphon Campus, Thailand
[2] Fluid Mechanics, Thermal Engineering and Multiphase Flow Research Lab (FUTURE) Department of Mechanical Engineering, King Mongkut's University of Technology Thonburi, Thailand
[3] Fellow of the Royal Institute, Academy of Science

Abstract

Adiabatic two-phase air-water flow experiments are conducted in this study. A fused silica channel, 120 mm long, with a diameter of 0.22 mm is used as the test section. The void fraction data obtained by image analysis correspond with the Amand-type correlation. The experimental frictional pressure drop data are compared with the homogeneous flow predictions. Several well-known two-phase viscosity models are evaluated in order to address the appropriate methods among them for application to micro-channels.

Key words: two-phase flow, micro-channel, void fraction, pressure drop

1. Introduction

Two-phase flow in micro-channel flow passages has been studied over the years. The clarifications of micro-scale effects on two-phase flow and heat transfer characteristics have become more necessary due to the rapid development of microstructure devices used for several engineering applications including medical devices, high heat-flux compact heat exchangers, and cooling systems of various types of equipment such as high performance micro-electronics, supercomputers, and high-powered lasers.

Several investigators have proposed criteria to address the definition of a micro-channel. The proposed channel classifications are often based on different dimensionless parameters. For instance, arbitrary channel classifications based on the hydraulic diameter D_h have been proposed. Mehendale et al. (2000) employed the hydraulic diameter as an important parameter for defining heat exchangers and Kandlikar (2002) proposed criteria for small flow channels used in engineering applications.

Two-phase flow and heat transfer characteristics in small channels such as micro-channels and mini-channels are likely to be strongly dependent on surface tension effects in addition to viscosity and inertia forces, resulting in significant differences in two-phase flow phenomena between ordinary sized channels and small channels.

In the past decade, there has been a relatively small amount of publications available for both mini-channels and micro-channels compared to those for ordinary sized channels.

Triplett et al. (1999a, 1999b) studied adiabatic two-phase air-deionized water (DI water) flow characteristics in micro-channels with hydraulic diameter ranging from 1.1 to 1.5 mm. The flow patterns observed were bubbly, slug, churn, slug-annular and annular. The measured void fraction and two-phase pressure drop in the relevant flow regimes were also investigated. The void fraction data were obtained based on the image analysis.

Serizawa et al. (2002) investigated the visualization of the two-phase flow pattern in circular micro-channels. The flowing mixture of air and water in channels of 20, 25 and 100 μm in diameter and that of steam and water in a channel of 50 μm in diameter were conducted experimentally. Two-phase flow patterns obtained from both air-water and steam-water flows were quite similar and their detailed structures were described. The study confirmed that the surface wettability had a significant effect on the two-phase flow patterns in very small channels.

Chung and Kawaji (2004) performed an experiment in order to distinguish two-phase flow characteristics in micro-channels from those in mini-channels. Four different circular diameters ranging from 50 to 526 μm were employed, to examine a scaling effect on nitrogen-DI water two-phase flow. The results including the flow patterns, void fraction and two-phase pressure drop were analyzed.

A flow visualization study to clarify the flow patterns of a vertical upward gas-liquid two-phase flow in rectangular mini-channels with hydraulic diameters ranging from 1.95 to 5.58 mm was carried out by Satitchaicharoen and Wongwises (2004). Air-water, air-20 wt.% glycerol solution, and air-40 wt.% glycerol solution were used as working fluids. In the experiments, they employed various rectangular test sections: 20 mm x 2 mm, 40 mm x 1 mm, 40 mm x 2 mm, 40 mm x 3 mm and 60 mm x 2 mm at an equal length of 1 m. The flow phenomena, which were classified as bubbly flow, cap-bubbly flow, slug flow, churn flow and annular flow, were observed and recorded by a high-speed camera. The effects of gap size, channel width and liquid viscosity on the flow pattern transitions were also discussed.

Saisorn and Wongwises (2008) reported the influence of the working fluid on flow characteristics in a 0.53 mm diameter channel. Air, nitrogen gas, water and de-ionized water were used as working fluids. The results of the two-phase air-water system were found to agree with those of working fluids other than air-water mixture. A new correlation was also developed based on their experimental data.

From the above review of the literature, the two-phase flow phenomena in micro-channels are not entirely consistent with those in ordinary sized channels. However, some experimental data for micro-channels showed fair agreement with predictions developed based on ordinary sized channels. In general, the prediction methods derived from the separated flow assumption were considered to compare with the data, whereas the homogeneous flow assumption seemed to be unattractive for previous researchers. This is possibly due to the fact that the observed flow patterns are much less homogeneous under different conditions. Interestingly, it should be noted from Chung and Kawaji (2002) and Saisorn and Wongwises (2008) that although their observed flow patterns were not perfectly homogeneous, the measured void fractions for channels with diameters larger than 0.1 mm were found to vary linearly with volumetric qualities. Such a linear relationship between the void fraction and volumetric quality indicates that two-phase flow behavior is not far from the homogeneous flow assumption. The current work is, therefore, aimed at examining the applicability of several widely used viscosity models to the pressure drop prediction of air-water flow through a 0.22 mm diameter channel.

2. Experimental apparatus and procedure

The experiments dealing with pressure drop measurements were carried out using the apparatus along with the instruments shown in Fig. 1. Air and water are used as working fluids in the system. Instead of a conventional pump, which may contribute to pulsation and fluid contamination, air and the liquid-filled tank are combined and operated as a pneumatic pump to supply a constant flow rate of liquid through the test section. The mixing chamber is designed to introduce the air-water mixture smoothly along the channel. The mixture flows freely from the channel outlet where atmospheric pressure is realized. The gas flow rates were able to be measured by four sets of rotameters within the range of 5-50 sccm, 0.05-0.5, 0.2-2.0, 1-10 SCFH, respectively. For liquid flow rate measurements, an electronic balance (320 ± 0.001 g) was used to measure the weight of the liquid flowing freely from the outlet over a period of time. The test section used in this work is a fused silica channel with a diameter of 0.22 mm and a length of 120 mm. The single-phase and two-phase pressure drops across the test section were determined by two pressure transducers installed at the channel inlet. The low range pressure transducer was calibrated from 0 to 250 kPa with a ± 0.5 kPa accuracy and the high range one was calibrated from 0 to 1000 kPa with a ± 2 kPa accuracy. Type T thermocouples were used to measure fluid temperatures. The degree of uncertainty of the temperature measurements was ± 0.1°C.

The single-phase flow experiments with different fluids were the first to be performed. Following this, the two-phase flow experiments were conducted at various gas and liquid flow rates. In this work, the gas flow rate was increased by small increments, while the liquid flow rate was kept constant at a pre-selected value. The system was allowed to approach steady conditions before the fluid flow rates, flow patterns and pressure drops were recorded.

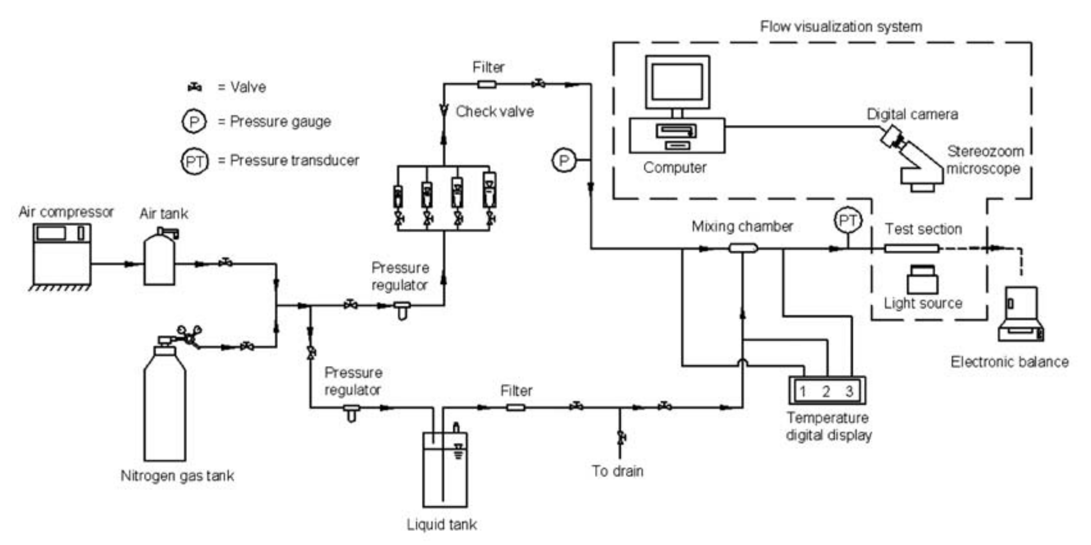


Figure 1 *Schematic diagram of test facility.*

3. Results and discussion

3.1. Void fraction

Void fraction is the fraction of channel cross-sectional volume that is occupied by the gas phase. This void fraction is one of the most important parameters used to evaluate the pressure drop components existing in two-phase flow in various channels. In the case of a horizontal channel, for instance, the void fraction is required before calculating the accelerational pressure drop.

For channels with hydraulic diameters of less than 1 mm, it may be convenient to estimate void fraction by image analysis. Regarding the flow patterns, observed from the presented channel, which are throat-annular flow, annular flow and annular-rivulet flow, the void fraction is the average value estimated from around 50-70 photographed images. The image analysis is considered by assuming symmetrical volumes, covering spherical and ellipsoidal segments as well as cylinders, formed by the gas-liquid interface. The volumetric void fraction was determined, based on the micrometer scale with an accuracy of ± 0.05 mm.

The void fraction data were found to agree well with the Armand-type correlation of Eq. (1) recommended for small channels.

$$\alpha = 0.833\beta \tag{1}$$

where α represents volumetric void fraction and β stands for volumetric quality.

The linear void fraction distribution was also reported by Saisorn and Wongwises (2008) but their data corresponding to a 0.53 mm diameter channel are very compatible with the homogeneous flow model ($\alpha = \beta$). Their void fraction val ues are slightly larger than the ones presented. Such deviations are due to the fact that for a larger diameter, a highly deformed gas-liquid interface is observed and hence the gas volume is decelerated through the liquid, resulting in the increment of residence time for gas volume in the field of view. The appearance of the gas volume with higher residence time indicates the relative high void fraction.

Although the data presented do not correspond well with the homogeneous flow model, the void fraction still varies linearly with volumetric quality. This implies that the slip ratio is not very large and that the pressure drop data may possibly be predicted by the methods developed from the homogeneous flow assumption. Several widely used viscosity models will be examined in the next section.

3.2 Frictional pressure drop

Prior to obtaining data for the two-phase frictional pressure drop, measurements of the total pressure drop are taken under various sets of different conditions. In this work, the total pressure drop of two-phase flow in a horizontal channel is composed of three terms: frictional pressure drop, accelerational pressure drop and pressure drop caused by the abrupt flow area. The latter component can be evaluated from an empirical correlation proposed by Abdelall et al. (2005). By subtracting the accelerational term and sudden contraction component from the total pressure drop, the frictional pressure drop data were obtained. Further details regarding the calculation method are available in Saisorn and Wongwises (2009). The frictional pressure drop data obtained are subsequently compared with the homogeneous flow predictions, taking into account several existing viscosity models.

The homogeneous flow model assumes that gas and liquid phases flow with equal velocity. The gas-liquid mixture is considered as a single-phase flowing with average fluid properties.

For pressure drop calculations based on the homogeneous flow, it follows that

$$-\frac{dP_f}{dz} = \frac{f_{TP} G^2}{2D\rho_H} \tag{2}$$

$$\rho_H = \left[\frac{x}{\rho_G} + \frac{(1-x)}{\rho_L}\right]^{-1} \tag{3}$$

In Eqs. (2) and (3), $(-dP_f/dz)$ is the two-phase frictional pressure gradient, G is mass flux, D is the channel diameter, x is mass quality, ρ_H is the average density of the homogeneous fluid, and ρ_L and ρ_G are liquid and gas densities, respectively. f_{TP} shown in Eq. (2) represents the two-phase Darcy friction factor which is a function of the two-phase Reynolds number:

$$Re_{TP} = \frac{GD}{\mu_{TP}} \tag{4}$$

For laminar flow ($Re_{TP} \leq 2100$),

$$f_{TP} = \frac{64}{Re_{TP}} \tag{5}$$

For turbulent flow ($Re_{TP} < 100{,}000$) in a smooth channel,

$$f_{TP} = \frac{0.3164}{Re_{TP}^{0.25}} \tag{6}$$

where μ_{TP} presented in Eq. (4) is two-phase viscosity. Several two-phase viscosity models proposed by different researchers are given in Eqs. (7) – (11).

McAdams et al. model (1942):

$$\frac{1}{\mu_{TP}} = \frac{x}{\mu_G} + \frac{(1-x)}{\mu_L} \tag{7}$$

Lin et al. model (1991):

$$\mu_{TP} = \frac{\mu_L \mu_G}{\mu_G + x^{1.4}(\mu_L - \mu_G)} \tag{8}$$

Cicchitti et al. model (1960):

$$\mu_{TP} = x\mu_G + (1-x)\mu_L \tag{9}$$

Dukler et al. model (1964):

$$\mu_{TP} = \beta\mu_G + (1-\beta)\mu_L \tag{10}$$

Beattie and Whalley model (1982):

$$\mu_{TP} = \beta\mu_G + (1-\beta)(1+2.5\beta)\mu_L \tag{11}$$

In the above equations, β is volumetric quality, and μ_G and μ_L represent gas and liquid viscosities, respectively.

The frictional pressure drop data are compared with the predictions with different viscosity models as presented in Figs. 2-6 which contain the mean absolute error (MAE) providing the predictive accuracy of the corresponding models. In general, the agreement between the predictions and the data presented is not good.

Only methods proposed by McAdams et al. (1942) and Beattie and Whalley (1982) were found to be roughly predictable. The comparisons illustrate that the viscosity model developed by McAdams et al. (1942) gives the best prediction, with MAE of 46.9% and 67.1% of the predicted data falling within a ±40% error band. With MAE of 44%, the method of Beattie and Whalley (1982), the second best prediction, captures 29.4% of the data within a ±40% error band.

As seen from the models shown in Eqs. (7) - (11), mass quality or volumetric quality is an important parameter in determining the two-phase viscosity. The models taking into account the mass quality tend to over-predict the data as illustrated in Figs. 3 and 4. As presented in Figs. 5 and 6, on the contrary, the models based on volumetric quality give under-prediction in comparison to the experimental results.

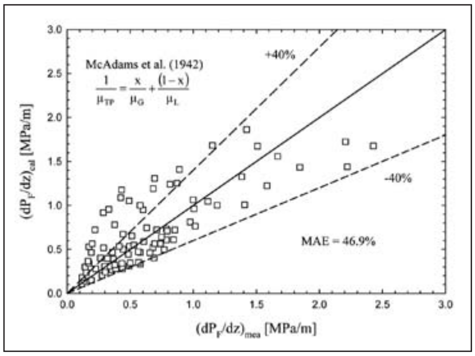
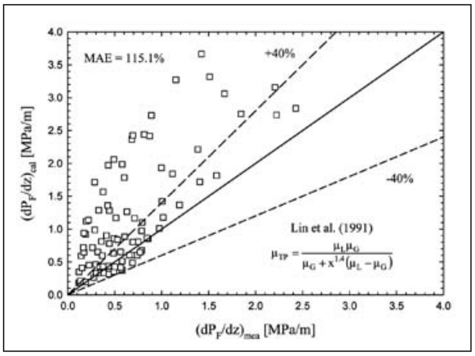


Figure 2

Experimental data vs. predicted pressure drop with McAdams et al. model [11].



Fiure 3

Experimental data vs. predicted pressure drop with Lin et al. model [12].

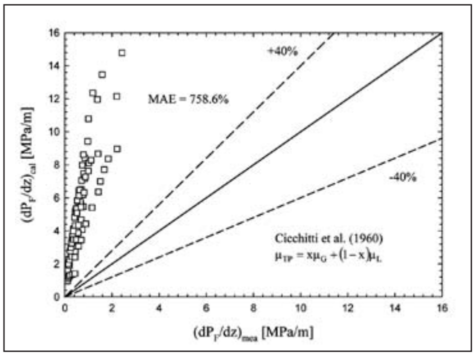


Figure 4

Experimental data vs. predicted pressure drop with Cicchitti et al. model [13].

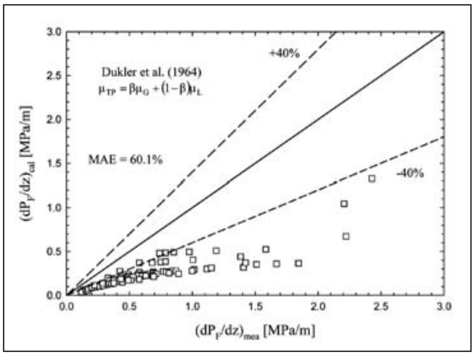


Figure 5

Experimental data vs. predicted pressure drop with Dukler et al. model [14].

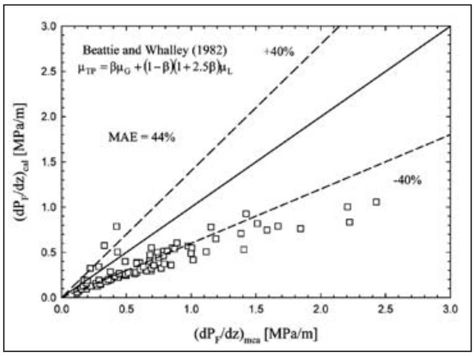


Figure 6

Experimental data vs. predicted pressure drop with Beattie and Whalley model [15].

4. Conclusion

Two-phase air-water flow is carried out in a channel with a diameter of 0.22 mm which is made of fused silica. Void fraction data are obtained based on image analysis. The void fraction is in a linear relationship with volumetric quality. The two-phase frictional pressure drop data are obtained by subtracting the accelerational term and the sudden contraction component from the total pressure droop. The capability of several well-known two-phase viscosity models for predicting pressure drop in the present channel is analyzed by comparing their predictions with experimental results.

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