

Measurement and Correlation of Pressure Drop for Gas-Liquid Two-phase Flow in Rectangular Microchannels*

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Abstract The pressure drop of gas-liquid two-phase flow in microchannel is of fundamental importance in heat and mass transfer processes. In this work, the pressure drop of gas-liquid two-phase flow in horizontal rectangular cross-section microchannels was measured by a pressure differential transducer system. Water, ethanol and *n*-propanol were used as liquid phase to study the effects of capillary number on pressure drop; air was used as the gas phase. Four microchannels with various dimensions of $100\ \mu\text{m} \times 200\ \mu\text{m}$, $100\ \mu\text{m} \times 400\ \mu\text{m}$, $100\ \mu\text{m} \times 800\ \mu\text{m}$ and $100\ \mu\text{m} \times 2000\ \mu\text{m}$ (depth $\times$ width) were used for determining the influence of configuration on the pressure drop. Experimental results showed that in micro-scale, the capillary number also affected the pressure drop remarkably, and in spite of only one-fold difference in aspect ratio, the variation of pressure drop reached up to near three times under the same experimental conditions. Taking the effects of aspect ratio and surface tension into account, a modified correlation for Chisholm parameter C in the Chisholm model was proposed for predicting the frictional multiplier ϕ_f^2 , and the predicted values by the proposed correlation showed a satisfactory agreement with experimental data.

Keywords pressure drop, rectangular cross-section microchannel, surface tension, configuration influence, Chisholm parameter C

1 INTRODUCTION

Over recent decades, microchemical technology has received increasing attention as an innovation of traditional chemical processes with more and more social and environmental concerns. Miniaturization of equipments into micro processes creates high efficiency, less pollution and operating safety [1–9]. As well known, gas-liquid two-phase flow remains essentially important in microchemical technology, and the pressure drop of gas-liquid two-phase flow is one of the most key parameters and has been extensively studied both experimentally and theoretically in the literature [10–13], in which rectangular microchannels were most frequently adopted due to easy fabrication and simple configuration. The rectangular channels can be fabricated on the surface of equipments at higher density levels compared to trapezoidal channels, which is important for increasing the interfacial area-to-volume ratio for a given substrate surface area [14]. Unfortunately, although many empirical correlations for predicting the pressure drop of gas-liquid two-phase flow in microchannels have been developed from different experimental and theoretical aspects, fewer studies have concerned the configurational impact on pressure drop, particularly the effect of the depth-to-width ratio of rectangular microchannel. Up to now, no unified approach may describe satisfactorily the geometrical effect on pressure drop under micro-scale condition, and the understanding of related knowledge is still lacking.

During early years, Lockhart and Martinelli [15] had put first forward a correlation for estimating the

two-phase frictional pressure gradient by introducing a Martinelli parameter X to the two-phase multiplier ϕ_f^2 . Chisholm [16] related ϕ_f^2 versus X by introducing another parameter, *i.e.*, Chisholm factor C , whose value depends dramatically on the flow conditions of liquid and gas phase ($C=5\text{--}20$). Successively, Wambsganss *et al.* [17], Mishima *et al.* [18], Lee and Lee [19], Ide *et al.* [20], Chen *et al.* [21] and Singh *et al.* [14] further studied gas-liquid two-phase flow in rectangular microchannels, and several modified correlations about the multiplier ϕ_f^2 or the Chisholm factor C were correspondingly proposed. However, all these correlations were resulted from the experiments of two-phase flow in channels with hydraulic diameters larger than 1 mm. For microchannels with hydraulic diameter of $100\ \mu\text{m}$ magnitude, little information is available in the literature.

In this work, the pressure drop of air-water, air-ethanol and air-*n*-propanol two-phase flow in four adiabatic horizontal rectangular microchannels was investigated experimentally, and the hydraulic diameters of four microchannels were all of $100\ \mu\text{m}$ magnitude. The influences of aspect ratio of microchannels and capillary number on pressure drop were studied, and a new correlation of Chisholm factor C was developed.

2 EXPERIMENTAL

Figure 1 illustrates the microchannel chips. They were fabricated first with etching technique, and then the mechanical method was applied to produce and polish the microchannels with rectangular cross-section.

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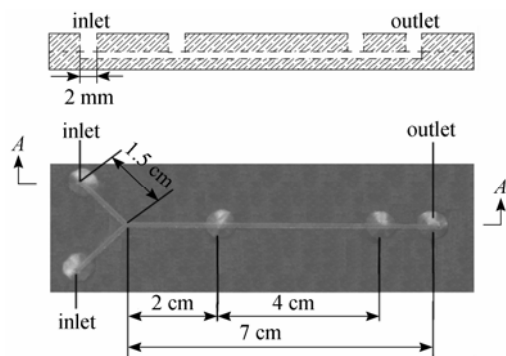


Figure 1 The microchannel chip

The length of inlets and two-phase mixing section are 1.5 cm and 7 cm, respectively. The angle of the Y-junction is 90°. The dimensions of cross-sections for four microchannels are 100 μm $\times$ 200 μm (depth $\times$ width), 100 μm $\times$ 400 μm , 100 μm $\times$ 800 μm and 100 μm $\times$ 2000 μm (named Microchannel I, Microchannel II, Microchannel III and Microchannel IV, respectively) with hydraulic diameters of 133.3, 160, 177.8 and 190.5 μm , and corresponding aspect ratios are 0.5, 0.25, 0.125 and 0.05, respectively. A pressure differential transducer was used to measure the pressure drops across a 40 mm length of microchannels. The upstream spot of the transducer situated 20 mm from the Y-junction, and downstream one 10 mm to the outlet. Table 1 lists the viscosity and surface tension of water, ethanol and *n*-propanol at 20 °C.

Figure 2 shows the schematic flow sheet of the experiment. Gas and liquid phases were driven by micro-infusion pumps (WZ-50C6, Zhejiang University Medical Instrument Co., Zhejiang, China) into the microchannel at set flow rates. The fluids were conveyed into the Y-junctions of microchannel chips by PVC circular tubes with 0.5 mm internal diameter, and

Table 1 The viscosity and surface tension of liquid phase used in experiments

	Viscosity $\mu\text{Pa}\cdot\text{s}$	Surface tension $\sigma/\text{N}\cdot\text{m}^{-1}$	μ/σ
water	1.005×10^{-3}	72.8×10^{-3}	0.0138
ethanol	1.2×10^{-3}	22.27×10^{-3}	0.0539
<i>n</i> -propanol	2.256×10^{-3}	23.71×10^{-3}	0.0952

after mixing of gas and liquid, the two-phase flow patterns were observed and recorded by a high-speed camera (2500 fps). Two filters were installed on the imported connecting tubes to prevent from being blocked in microchannels. The actual flow rates of liquid phases were measured by an electronic balance (weighing the accumulated liquid phase in a collector over a period of time). The actual gas flow rates were determined in terms of the set flow rate values of the pump. It takes about ten minutes for the gas-liquid two phase flow reaching steady and the pressure drop across the microchannel becoming nearly constant. The error margin of superficial velocity was $\pm 2\%$. The range of pressure differential transducers was 0–350 kPa, with error margin of ± 0.1 kPa. Experiments were carried out at room temperature 298.15 K and atmospheric pressure. The total air and water mass flux G was changed from 20 to 300 $\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ and the gas phase quality x was from 0.001 to 0.3.

3 RESULTS AND DISCUSSION

3.1 Frictional pressure drop for single-phase liquid flow

The total two-phase pressure drop of microchannel is given as

$$\Delta p_t = \Delta p_F + \Delta p_A + \Delta p_C \quad (1)$$

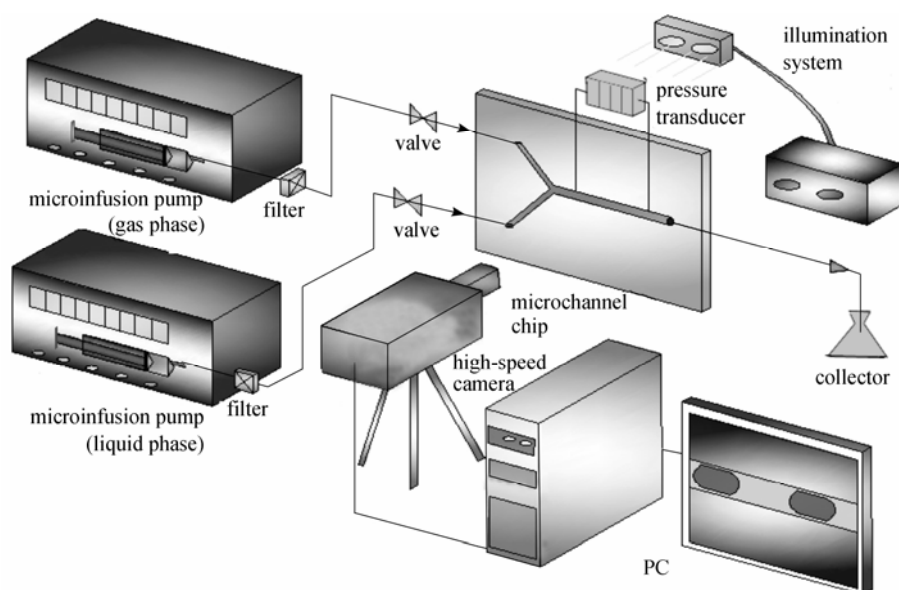


Figure 2 Schematic flow sheet of the experiment

in which Δp_F is the frictional pressure drop, Δp_A the acceleration pressure drop, and Δp_C the pressure drop caused by contraction from the connecting tubes into the microchannel. Compared to Δp_F , Δp_A and Δp_C are negligible, therefore the frictional pressure drop could be considered approximately as the total two-phase pressure drop [17–20]. For prediction of two-phase frictional pressure drop in a channel, it is necessary to pre-estimate the friction factor of single phase flow in the same channel, which is defined as

$$f = \frac{\Delta p_F d_h}{2L\rho U^2} \quad (2)$$

The friction factor for the laminar flow of single phase through the rectangular channels proposed by Harnett and Kostic [22] was adopted:

$$f = 24(1 - 1.3553A + 1.946A^2 - 1.7012A^3 + 0.9564A^4 - 0.2537A^5) / Re \quad (3)$$

For turbulent flow of single phase, the friction factor can be expressed by the Blasius equation:

$$f = 0.079 Re^{-0.25} \quad (4)$$

where Re is the Reynolds number, $Re = \rho U d_h / \mu$. In this work, water, ethanol and *n*-propanol were used respectively for measuring the friction factors in microchannels. The experimental friction factors of water are plotted in Fig. 3, in which the straight lines are the friction factors for laminar and turbulent flows predicted by Eqs. (3) and (4), respectively. Obviously,

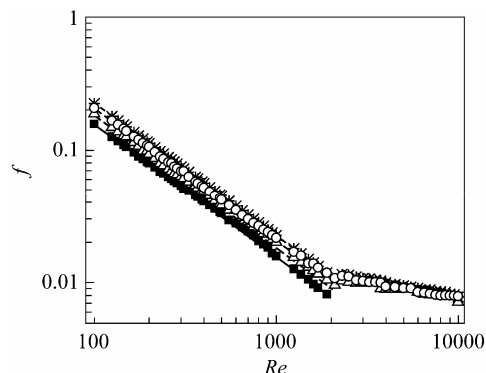


Figure 3 Friction factors for single phase water flow in microchannels

■ microchannel I; △ microchannel II; ○ microchannel III; * microchannel IV;
— $f = 15.55/Re$; ---- $f = 18.23/Re$; - - - $f = 20.59/Re$;
- · - · $f = 22.49/Re$; - · - · $f = 0.079/Re^{0.25}$

f decreases with the increase of A , and the friction factors of ethanol and *n*-propanol presented a similar relationship with A (not plotted here). The experimental results agree favorably with the lines, that validates the accuracy of our experiments.

3.2 Frictional pressure drop for two-phase flow

Figures 4 (a)–(d) illustrate the experimental results of pressure drop for air-water, air-ethanol and

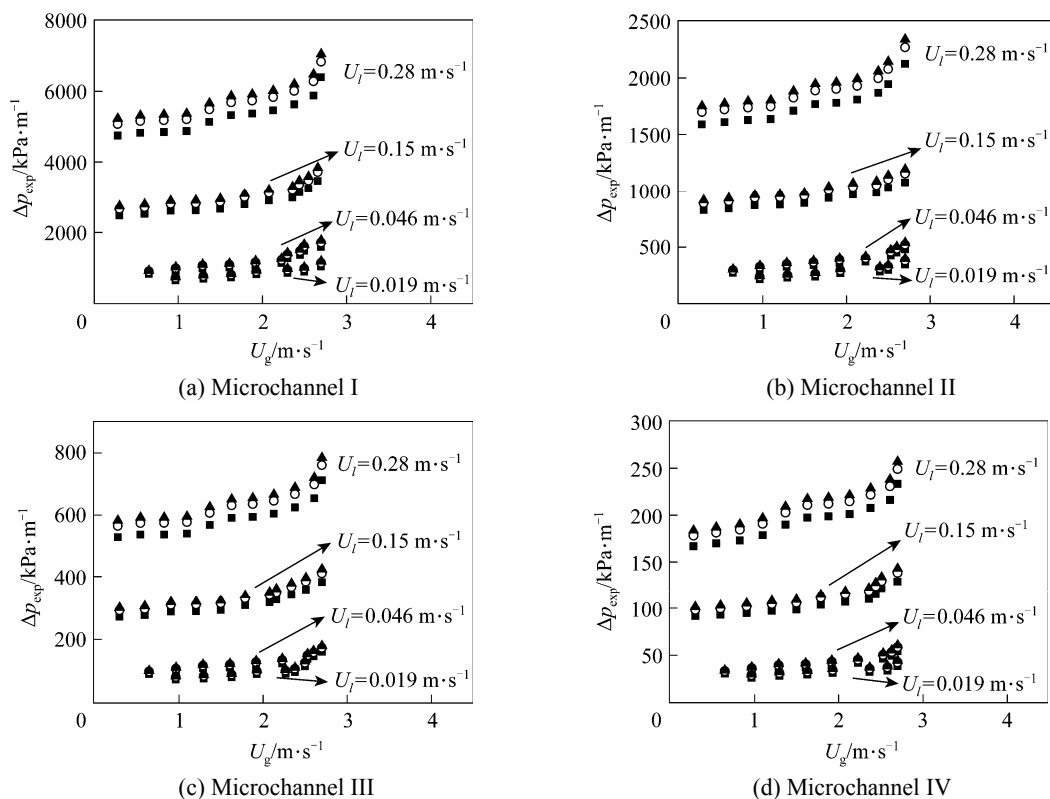


Figure 4 Pressure drop for three different component systems in four various microchannels

■ air-water; ○ air-ethanol; ▲ air-*n*-propanol

air-*n*-propanol two-phase flow in four different microchannels, showing that the effect of surface tension or so called the capillary number Ca ($Ca = \mu U / \sigma$) on pressure drop could not be neglected. The hydraulic diameters of four microchannels are 133.3, 160, 177.8 and 190.5 μm , respectively. Their differences between two adjacent microchannels are all less than 20%, but the pressure drop differences for two adjacent microchannels varied near three times in contrast with one-fold change in aspect ratio. It denotes that the obvious influence on pressure drop is primarily due to aspect ratio rather than hydraulic diameter.

The influence of aspect ratio of microchannels on the frictional pressure drop is due to changing the length of gas bubble and liquid slug in slug flow and the thickness of liquid film in annular flow. The configuration of microchannels became flatter and flatter from microchannels I to IV, therefore, the gas phase and liquid phase tended more and more to adhere to the wide walls, and the length of gas bubble and liquid slug in slug flow became longer from microchannel I to IV, which resulted in gradually less frictional force between gas and liquid phases and that between the thin liquid film and channel walls (shown in Fig. 5). In the same microchannel, for a given gas and liquid flow rates, the liquid phase capillary number of *n*-propanol has the highest value among three systems but still far smaller than 0.1, it means that the influence of surface tension became gradually remarkable from air-water to air-ethanol and to air-propanol system, as a consequence, leading to the shorter and shorter length of gas bubble and liquid slug, which increased two-phase interface and frictional force inside the microchannels (shown in Fig. 6), therefore, the air-*n*-propanol system appeared the highest frictional pressure drop among three systems.

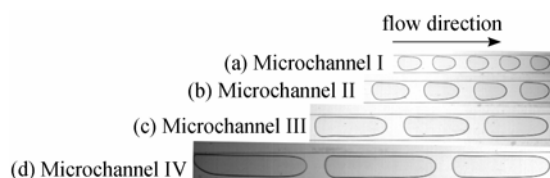


Figure 5 Air-ethanol gas-liquid two-phase flow patterns in microchannels ($U_l = 0.15 \text{ m}\cdot\text{s}^{-1}$, $U_g = 1.5 \text{ m}\cdot\text{s}^{-1}$)

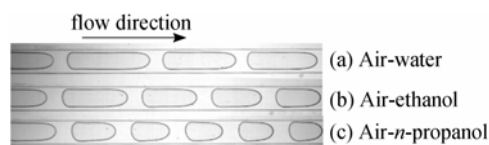


Figure 6 Gas liquid two-phase flow patterns in microchannel IV ($U_l = 0.046 \text{ m}\cdot\text{s}^{-1}$, $U_g = 1.0 \text{ m}\cdot\text{s}^{-1}$)

Recently, large amounts of work have been focused on the prediction of the gas-liquid two-phase frictional pressure drop in microchannels. In previous studies, the homogeneous flow model has been validated by experiments [23, 24]. Gas and liquid two phases are uniformly mixed as the gas phase dispersed

in liquid phase as small bubbles in the homogeneous flow model, however, two phases were not uniformly mixed (shown in Figs. 5 and 6) in the present experiments. Clearly, the homogeneous flow model is unsuitable for the present situations.

Based on the assumption of separated flow, the Lockhart and Martinelli correlation could well describe the vertical air-water two-phase flow in miniature triangular channels with $d_h = 0.87\text{--}2.89 \text{ mm}$ [25]. The definition of Martinelli parameter X could be expressed as:

$$X^2 = (\Delta p_F / L)_l / (\Delta p_F / L)_g \quad (5)$$

Meanwhile, the two-phase multiplier ϕ_l^2 is also defined as

$$\phi_l^2 = (\Delta p_F / L)_t / (\Delta p_F / L)_l \quad (6)$$

Chisholm [16] related ϕ_l^2 versus X by introducing another parameter, Chisholm factor C :

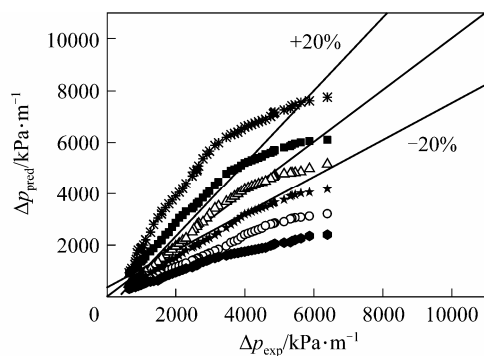
$$\phi_l^2 = 1 + (C / X) + (1 / X^2) \quad (7)$$

Wambsganss *et al.* [17] measured the two-phase frictional pressure drop in a single small channel with cross section of $19.05 \times 3.18 \text{ mm}$ and proposed a modified expression for Chisholm factor C . Mishima *et al.* [18] conducted a series of two-phase flow experiments in narrow rectangular ducts with the width of 40 mm and gaps of 1.0, 2.4 and 5.0 mm, and modified the Chisholm factor C by introducing hydraulic diameter. Lee and Lee [19] investigated the pressure drop for air-water two-phase flow in rectangular microchannels with small gaps (0.4–4 mm) while the width of microchannels being fixed at 20 mm, and proposed a new correlation of parameter C taking the effects of mass flux and gap size into account. Ide *et al.* [20] investigated the impact of aspect ratio on pressure drop in adiabatic rectangular microchannels, with the channel diameters larger than 1 mm. The frictional multiplier ϕ_l was proposed in vertical rectangular channels, where gravity has an important influence, but in micro-scale and horizontal microchannels the gravity is negligible. Chen *et al.* [21] tested single-phase and air-water two-phase frictional pressure drop in three rectangular channels with channel widths of 3, 6 and 9 mm and fixed gap of 3 mm. A modified C factor, considering the effect of aspect ratio, was proposed for channel diameter larger than 1 mm. Singh *et al.* [14] studied the influence of aspect ratio on pressure drop of vapor-water in heating microchannels, but they did not investigate the frictional pressure drop under adiabatic situation. Table 2 gives the above correlations of the literature.

Figure 7 shows the comparisons of predicted results of two-phase frictional pressure drop by correlations in Table 2 with the experimental results of air-water system. The results of air-ethanol and air-*n*-propanol systems showed the same trends as the air-water system and accordingly were not presented here. Table 3 lists the ranges of mean deviations between predictions by correlations in the Table 2 and experimental

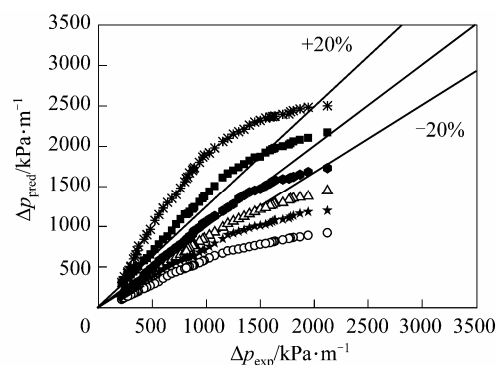
Table 2 Correlations proposed in literature

Authors	Correlation	Parameters
Wambsganss <i>et al.</i> [17]	$C = ax^b$	$a = -2.44 + 0.00939Re_l$, $b = -0.938 + 0.000432Re_l$
Mishima <i>et al.</i> [18]	$C = 21[1 - \exp(-0.27d_h)]$	
Lee and Lee [19]	$C = B\lambda^q Ca_l^r Re_l^s$	$\lambda = \mu_l^2 / (\rho_l d_h \sigma)$, $Ca_l = \mu_l U_l / \sigma$
Ide <i>et al.</i> [20]	$\phi_l = 0.2485A^{-0.355} (U_l / \sqrt{gd_h})^{-0.233} Re^{3/8}$ $\phi_l = 0.0848A^{-0.145} [(U_g + U_l) / U_l]^{-0.425} Re^{3/8}$	
Chen <i>et al.</i> [21]	$C = mx^n$	$m = 5.55 - 0.7555A^{-0.805} + 0.00439Re_l$, $n = 0.1001 + 0.0005A^{0.895}$



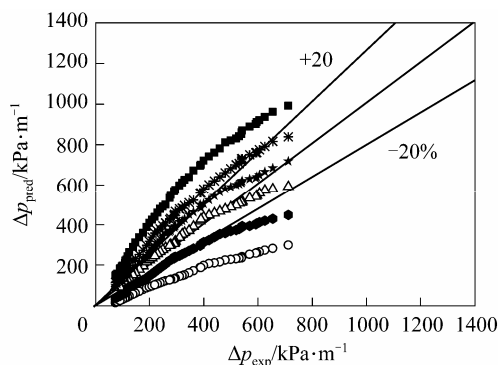
(a) Microchannel I

mean deviation: ■ Ref. [19], 31.325%; ○ Ref. [21], 42.97%;
△ Ref. [17], 9.3%; ★ Ref. [18], 24.78%; ● Ref. [20] in LL
flow pattern, 54.55%; * Ref. [20] in LT flow pattern, 72.85%



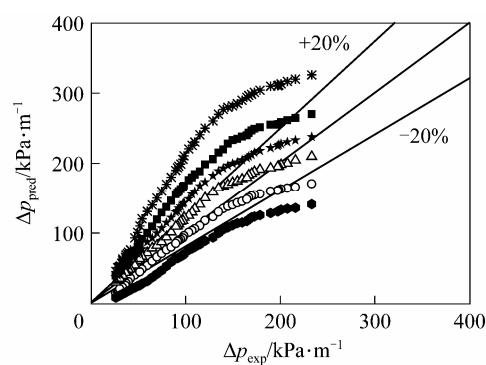
(b) Microchannel II

mean deviation: ■ Ref. [19], 31.831%; ○ Ref. [21], 45.62%;
△ Ref. [17], 17.38%; ★ Ref. [18], 26.93%; ● Ref. [20] in LL
flow pattern, 8.72%; * Ref. [20] in LT flow pattern, 73.49%



(c) Microchannel III

mean deviation: ■ Ref. [19], 84.98%; ○ Ref. [21], 57.01%;
△ Ref. [17], 10.89%; ★ Ref. [18], 27.08%; ● Ref. [20] in LL
flow pattern, 28.47%; * Ref. [20] in LT flow pattern, 27.95%



(d) Microchannel IV

mean deviation: ■ Ref. [19], 58.51%; ○ Ref. [21], 12.36%;
△ Ref. [17], 19.36%; ★ Ref. [18], 40.97%; ● Ref. [20] in LL
flow pattern, 37.96%; * Ref. [20] in LT flow pattern, 93.7%

Figure 7 Comparison between predictions by correlations in the literature and experimental results in the air-water system

Table 3 Mean deviations between predictions of correlations in Table 2 and experimental results

Microchannels	Air-water	Air-ethanol	Air- <i>n</i> -propanol
I	9.3%–72.85%	15.68%–77.54%	19.93%–76.91%
II	8.72%–73.49%	17.53%–76.49%	18.56%–77.93%
III	10.89%–84.98%	16.49%–79.58%	21.23%–85.46%
IV	12.36%–93.7%	17.82%–90.56%	22.46%–89.67%

results. In fact, the surface tension becomes very important in fluid flow, and always controls the characteristics of fluid flowing in microchannels. All of the hydraulic diameters of microchannels used in experiments were less than 200 μm , and the capillary numbers were all much smaller than 0.1. Therefore, the capillary number is as important as the Reynolds number in this situation, as shown in the experimental results of three systems.

The definition of the Martinelli parameter X is the ratio of the frictional pressure drops of the liquid phase to that of the gas phase. In fact, the single-phase frictional pressure drops are mainly determined by gas and liquid phase Reynolds number, and because the viscosity and density of liquid phase are much greater than those of gas phase, the Martinelli parameter X could be replaced by the liquid Reynolds number [18–20]. It can be seen from the Table 2 that, Lee and Lee [19] proposed the predicted correlation of C factor containing the Ca_l and Re_l but without aspect ratio A , Ide *et al.* [20] concluded the correlations containing the aspect ratio A and Re but without the Ca_l and the correlation of Chen *et al.* [21] also contained the aspect ratio A and Re_l but without the Ca_l . On the basis of above three correlations and considering the configuration effect of rectangular microchannels, the liquid phase Reynolds number and the capillary number on the pressure drop of gas-liquid two-phase flow in rectangular microchannels, we proposed a new correlation for C factor:

$$C = F(A, Ca_l, Re_l) = aCa_l^b \quad (8)$$

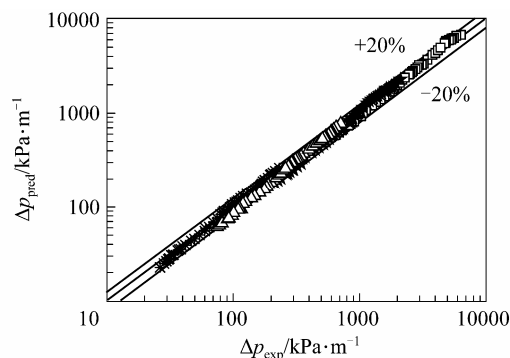
where $Ca_l = \mu_l U_l / \sigma$, $a = 7.59 - 0.4237A^{-0.9485} + 0.0023Re_l$ represents the influences of the aspect ratio and liquid phase Reynolds number on frictional pressure drop of gas-liquid two-phase flow, and $b = 0.223 + 0.2A^{0.9778}$ just confirms the importance of aspect ratio for frictional pressure drop in micro-scale. Parameter a and b were obtained through a least square regression of the experimental data. The comparisons of frictional pressure drop between the predicted values by Eq. (8) and experimental results for microchannel I, II, III and IV are shown in Fig. 8, and the mean deviations for air-water were 7.23%, 8.23%, 8.21% and 6.9%; for air-ethanol were 7.95%, 7.69%, 9.43% and 8.84%; for air-*n*-propanol were 8.43%, 9.58%, 7.61% and 9.77% in microchannel I, microchannel II, microchannel III and microchannel IV, respectively. Fig. 9 shows the comparisons of predictions by Eq. (8) with the experimental data in Refs. [17–21], and the mean deviations range from 12.76% to 19.22%. In summary, the proposed correlation shows good agreement with experimental data both in the present work and in the literature.

4 CONCLUSIONS

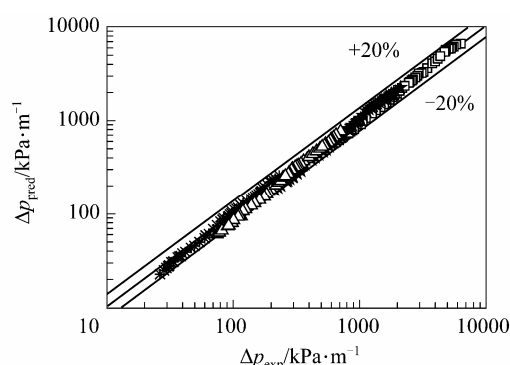
The frictional pressure drop for water, ethanol and *n*-propanol single-phase flow and air-water, air-ethanol and air-*n*-propanol two-phase flow in adiabatic horizontal rectangular microchannels were investigated experimentally, and the following summaries can be concluded.

(1) The measured friction factor f for water, ethanol and *n*-propanol single-phase could be well described in both the laminar and turbulent flows.

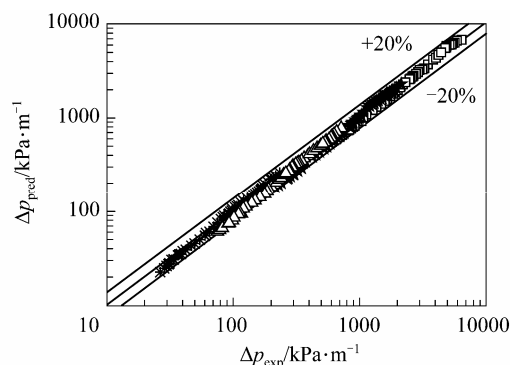
(2) The differences of pressure drop for all three binary systems were found to reach up to three times respectively in each of four microchannels, while the



(a) Predictions of Eq. (8) vs. experimental results for air-water two-phase flow
mean deviation: □ microchannel I 7.23%; ★ microchannel II 8.23%; △ microchannel III 8.21%; * microchannel IV 6.9%



(b) Predictions of Eq. (8) vs. experimental results for air-ethanol two-phase flow
mean deviation: □ microchannel I 8.03%; ★ microchannel II 7.68%; △ microchannel III 9.33%; * microchannel IV 8.54%



(c) Predictions of Eq. (8) vs. experimental results for air-*n*-propanol two-phase flow
mean deviation: □ microchannel I 7.77%; ★ microchannel II 9.68%; △ microchannel III 8.56%; * microchannel IV 7.32%

Figure 8 The comparisons of frictional pressure drop between the predicted values and experimental results

aspect ratio between adjacent two microchannels in turn for four microchannels is only one-fold difference. Furthermore, in micro-scale, the capillary number also affected the pressure drop remarkably. The experimental results were compared to various approaches

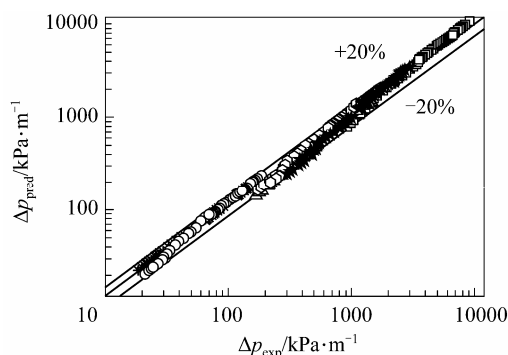


Figure 9 Predictions of Eq. (8) vs. experimental results in the literature

mean deviation: □ Ide *et al.* [20] in LT flow pattern, 13.39%; ○ Ide *et al.* [20] in LL flow pattern, 18.34%; △ Mishima *et al.* [18], 11.35%; ◐ Wambsganss *et al.* [17], 12.76%; * Chen *et al.* [21], 19.22%; ★ Lee and Lee [19], 18.53%

in the literature, however, none of correlations can satisfactorily predict the whole database under wide range of experimental conditions.

(3) A new correlation for the Chisholm factor C was proposed, taking the effects of the aspect ratio and the surface tension into account. The mean deviations between predicted values by the proposed correlation and the experimental results were all less than 10%, and always less than 20% for two-phase flows in the literature. This correlation could be applied to a very wide range of experimental conditions: the mass flux ($20 < G < 300 \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$), gas quality ($0.001 < x < 0.3$) and the aspect ratio ($0.05 < A < 0.5$).

NOMENCLATURE

A	aspect ratio of microchannels ($A = \text{channel height/channel width}$)
C	Chisholm factor
Ca_l	liquid phase capillary number ($Ca_l = \mu_l U_l / \sigma$)
d_h	hydraulic diameter of non-circular tubes, m
G	total mass flux, $\text{kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$
L	length of microchannel, m
Δp_{exp}	experimental pressure drops in microchannels, $\text{kPa} \cdot \text{m}^{-1}$
Δp_F	total frictional pressure drop in microchannel, $\text{kPa} \cdot \text{m}^{-1}$
$(\Delta p_F / L)_g$	frictional pressure drop of gas-phase flow in microchannels, $\text{kPa} \cdot \text{m}^{-1}$
$(\Delta p_F / L)_l$	frictional pressure drop of liquid single-phase flow in microchannels, $\text{kPa} \cdot \text{m}^{-1}$
$(\Delta p_F / L)_t$	frictional pressure drop of gas-liquid two-phase in microchannels, $\text{kPa} \cdot \text{m}^{-1}$
Δp_{pred}	predicted pressure drops in microchannels, $\text{kPa} \cdot \text{m}^{-1}$
Re	Reynolds number ($Re = \rho U d_h / \mu$)
U	gas and liquid total superficial flow velocities, $\text{m} \cdot \text{s}^{-1}$
U_g	gas superficial velocity, $\text{m} \cdot \text{s}^{-1}$
U_l	liquid superficial velocity, $\text{m} \cdot \text{s}^{-1}$
x	gas phase quality ($x = G_g / G$)
μ	fluid viscosity, $\text{Pa} \cdot \text{s}$
ρ	fluid density, $\text{kg} \cdot \text{m}^{-3}$
σ	surface tension, $\text{N} \cdot \text{m}^{-1}$

Subscripts

exp	experimental values
F	frictional
g	gas phase
h	hydraulic
l	liquid phase
pred	predicted values
t	gas and liquid total phase

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