An Evaluation of Correlations for Predicting Pressure Drop of Air-Water Flow in Narrow Rectangular Duct

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Abstract: Aiming at developing a more common method for predicting two-phase flow pressure drop for small channels, experiments on frictional pressure drop of air-water flow in a vertical narrow rectangular duct with a cross-section of 40 mm by 1.6 mm were conducted at atmospheric pressure. The mass flow rates of air and water covered the ranges from 0.03 to 12.5 kg/h and from 19 to 903 kg/h, respectively. It was found that the two-phase flow can be divided into three regions according to the liquid only Reynolds number, by which a modified Chisholm two-phase multiplier was proposed for predicting frictional pressure drop. Some leading correlations for predicting two-phase flow pressure drop were compared with the new correlation against current experimental data, the latter had and a mean deviation of 7.2%, showing a better agreement with the experimental results.

Keywords: Two-phase flow, Frictional pressure drop, Narrow rectangular duct, Two-phase friction multiplier.

1. INTRODUCTION

The prediction of pressure drop in two-phase flow system is of great importance in the design of two-phase flow systems, such as air-conditioning systems, steam generator and condenser, etc. In the past, most of the studies reported on the two-phase flow mechanism were about the circular tube larger than 10 mm in diameter [1]. In recent years, demands of compact and high efficiency heat exchanger have led to using of small diameter tubes in both high power electronic devices and air-conditioning applications due to their good heat transfer performance. Despite this advantage, an increase in pressure drop through the channels with smaller diameter is hardly to be avoided due to the increase of wall friction. Especially, inside the evaporators and condensers with small size heat transfer tubes, pressure drop of the two-phase mixture flows becomes even larger.

Extrapolations of the conventional pressure drop calculation methods to applications utilizing rectangular ducts with small hydraulic diameter are uncertain, and the frictional two-phase pressure drop correlations and the published experimental data for narrow rectangular ducts are very limited. Lowry and Kawaji [2] studied the flow patterns of the adiabatic current upward flow of air-water in a narrow passage between two flat plates, with gap widths of 0.5 mm, 1 mm and 2 mm, a predictive model describing transition to annular flow was developed and the pressure drop along the passage was also measured. Those authors compared their data with the Lockhart-Martinelli correlation and concluded that although the correlation represented the general trend of the data, it failed to predict the mass velocity effects. They found that the two-phase frictional multiplier was mainly dependent on the superficial gas velocity and less sensitive to superficial liquid velocity and gap width. Recently, Kumar *et al*. [3] studied void fraction and pressure drop characteristics of vertical air-water down flow in mini-channels. They described the hydrodynamics as a function of tube diameter and phase velocities for different plow patterns. Accordingly, they proposed respective mechanistic models to predict pressure drop for bubbly, slug, falling film and annular flow distributions.

Mishima and Hibiki [4] measured the flow regime, void fraction, slug bubble velocity and pressure loss in rectangular ducts with narrow gaps ranging from 1.0 to 5.0 mm, and large aspect ratios. They reported that the void fraction was well correlated by the drift flux model with the existing correlation for the distribution parameter, which was about 1.35, the frictional pressure loss was found to be well predicted by the Chisholm-Laird correlation, and the parameter C depends on the hydraulic diameter, decreasing from 21 to 0 as the hydraulic diameter decreases from 10 to 0.1 mm. Hamad *et al*. [5] compared their results of pressure drop of gas-liquid flow in horizontal pipes of different diameters from 12.7 to 25.4 mm with a number of empirical models. They found the drift-flux

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model and homogenous model were the most suitable models for pressure drop prediction compared with another models, such as Lockhart-Martinelli and Friedel model. Maqbool *et al*. [6] found Müller-Steinhagen and Heck [7] and Friedel [8] for two phase pressure drop well predicted their experimental data by studying two-phase flow boiling in a vertical circular stainless steel mini-channel with inner diameter of 1.70 mm.

Lee and Lee [1] performed a series of experiments using 4 rectangular channels, the gap between the upper and the lower plates of each channel ranges from 0.4 to 4 mm while the channel width being fixed to 20 mm, water and air were used as the test fluids. In their study, the two-phase frictional multiplier was expressed using the Lockhart-Martinelli type correlation but with the modification on parameter C, by which the effects of the mass flux and the gap size were considered. Zhang and Hibiki [9] explored the two-phase pressure drop and void fraction in mini-channels based on the separated flow model and drift flux model, via the artificial neural network method, they found that the non-dimensional Laplace constant is a main parameter to correlate the Chisholm parameter C as well as the distribution parameter C_0. Sun and Mishima [10] collected 2092 data of two-phase pressure drop from 18 published papers, eleven correlations and models for calculating the two-phase frictional pressure drop were evaluated based upon these data. They proposed a new modified Chisholm correlation, in which the Chisholm parameter C is a variable affected by the liquid Reynolds and the Laplace number in laminar region, C/X is greatly affected by the ratio of gas Reynolds and liquid Reynolds in turbulent flow region. Awad and Muzychka [11-12] provided some new insights on modeling two phase flows in mini-scale channels using homogeneous and L-M/Chisholm type models. They use an analogy thermal conductivity of porous media and viscosity in two-phase flow, and proposed some new definitions for two-phase viscosity, which can be used to calculate the two-phase frictional pressure drop using the homogeneous modeling approach; Later, they proposed an alternative approach for predicting two-phase flow pressure drop using superposition of three pressure gradients: single phase liquid, single phase gas, and interfacial pressure drop, which allows for the interfacial pressure drop to be easily modeled for each type of flow regime using one/two parameter model.

More recently, pressure drop of two-phase flow boiling in small channels receives more attention. Different flow regimes from pre-heating of sub-cooled water to dry-out in a tube of 19 mm in diameter were investigated by Sardeshpande *et al*. [13]. They found flow instability caused by the vapor generation was evident in flow pattern transition from stable single phase to repetitive pressure fluctuation pattern in two-phase flow boiling. Pan *et al*. [14] investigated the characteristics of flow boiling pressure drop in a microchannel heat sink which contains 14 parallel 0.15 × 0.25 mm rectangular microchannels. Results revealed that the pressure drop exhibited a trend of slight decrease and then sharp increase with the increase of heat flux under constant inlet temperature and mass flux. The Mass flux, heat flux, and inlet temperature played key roles in variation of pressure drop. Wang *et al*. [15] found that models of Quibén [16], Zhang and Hibiki [9], Sun and Mishima [10] and Lee and Lee [1] had a good prediction in pressure drop for steam condensation flow in vacuum horizontal tube of 18 mm in diameter.

In view of the previous investigations, it can be found that the Lockhart-Martinelli correlation for the two-phase frictional multiplier cannot well predict the two-phase pressure drop for the narrow rectangular ducts. All the above works have proved that the Chisholm parameter C is not a constant, but affected by the mass flow rate, Laplace constant and the gap size. Although existing experimental works have revealed some unique phenomena in mini-channels, no general theory or calculation model is available by far. In view of this, two-phase flow in a narrow rectangular duct with the cross-section of 40×1.6 mm^2 was studied to develop a more common method for predicting frictional pressure drop in narrow channels.

2. EXPERIMENTAL SYSTEM

A schematic diagram of the experimental apparatus is shown in Figure **1**. The system basically consists of four parts, water supply system, air supply system, the test section and data acquisition system. Air is supplied from a compressor passed through an air-holder, an air/liquid separator, a reducing valve (which keeps the air pressure less than 0.3 MPa), an air mass flowmeter, a ball valve, a check valve and was injected into the mixing chamber. Water flows through a water mass flowmeter and a control valve to the mixing chamber, the mixing chamber's configuration is shown in Figure

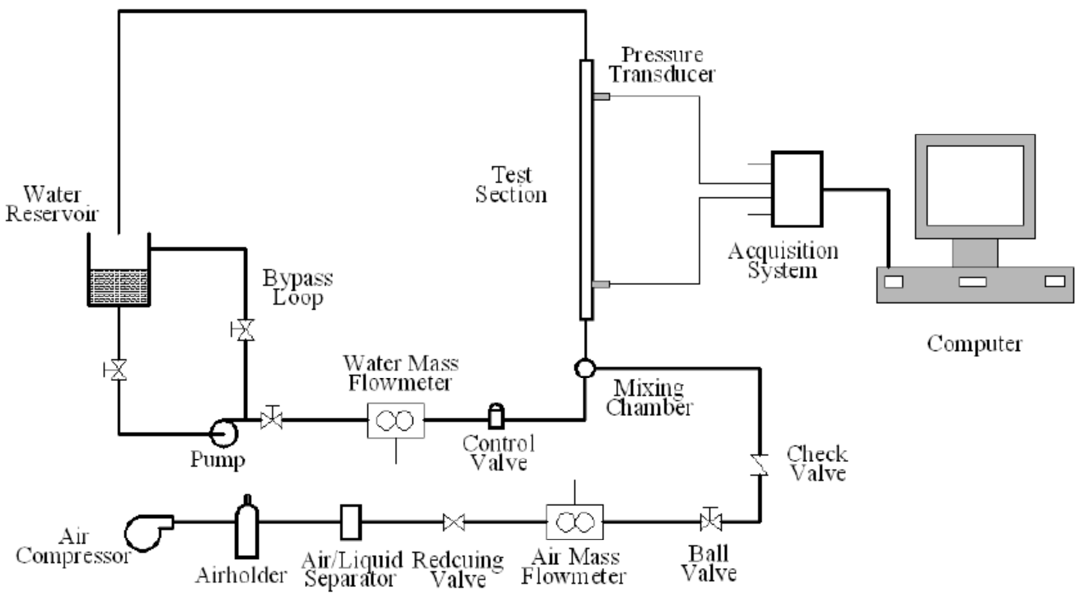

Figure 1: Schematic of experimental apparatus.

2. A branch pipe is connected to the main pipe for introducing air into the main stream. Small feeding holes were drilled through the main pipe wall to help form smaller bubbles. Air-water mixture then flows through the test section, after which water is returned to the water tank and air is vented to the atmosphere. The accuracy of the air and water mass flowmeters are within ±0.5% and ±0.1% of the span, respectively.

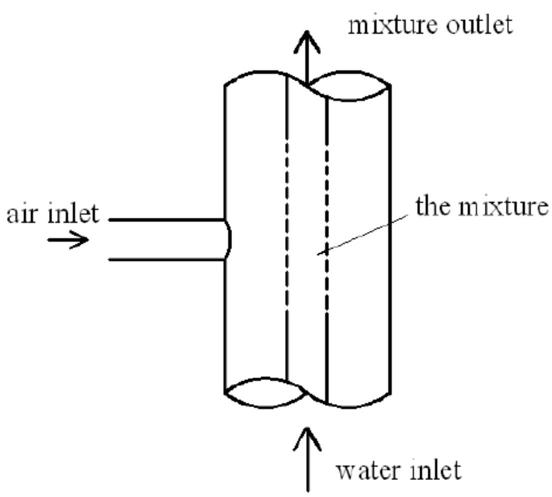

Figure 2: Configuration of the mixing chamber.

The test section is made of transparent organic glass, with the length of 2000 mm and with a cross-section of 40 mm×1.6 mm. Two pressure taps with the distance of 1500 mm were drilled on the wide side of the test section, as shown in Figure **3**. The pressure difference is measured by two pressure transducers (PR35X, manufactured by KELER) with measurement scales of 0~250 kPa (P1) and 0~100 kPa (P2), respectively. Both have the accuracy of 0.2% of the full scale. The pressure and flow rate signals were collected by using a NI data acquisition system (SCXI-1125, NATIONAL INSTRUMENTS) of which the sampling frequency is 256 HZ, and measurement period is 20 s for one experimental condition. The experiments were performed under the conditions of water mass flow rates from 19 to 903 kg/h, air flow rates from 0.03 to12.5 kg/h.

3. DATA REDUCTION

Two-phase pressure drop in vertical rectangular duct is caused by frictional on the wall $(-\mathrm{d}p/\mathrm{d}z)_\mathrm{f}$ (frictional pressure drop), static head $(-\mathrm{d}p/\mathrm{d}z)_\mathrm{g}$ (gravitational pressure drop) and acceleration $(-\mathrm{d}p/\mathrm{d}z)_\mathrm{a}$ (acceleration pressure drop) as expressed in eq. (1):

$$\left(-\frac{\mathrm{d}p}{\mathrm{d}z}\right)_{\mathrm{tp}} = \left(-\frac{\mathrm{d}p}{\mathrm{d}z}\right)_{\mathrm{f}} + \left(-\frac{\mathrm{d}p}{\mathrm{d}z}\right)_{\mathrm{g}} + \left(-\frac{\mathrm{d}p}{\mathrm{d}z}\right)_{\mathrm{a}} \tag{1}$$

In the present adiabatic air-water two-phase flow system, no heat transfer is involved. Hence, the mass quality does not change along the flow direction and the acceleration pressure drop is neglected here. Eq. (1) is simplified to:

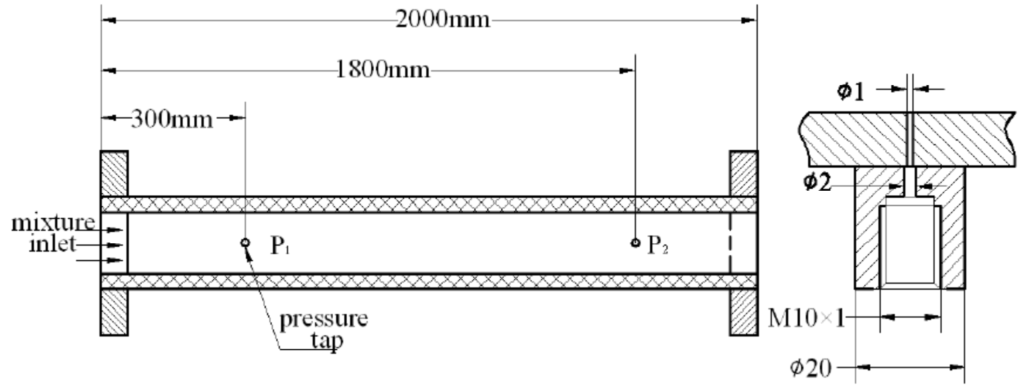

Figure 3: Test section and the pressure tap.

$$\left(-\frac{dp}{dz}\right)_{tp} = \left(-\frac{dp}{dz}\right)_{f} + \left(-\frac{dp}{dz}\right)_{g} = \Delta P_f + \Delta P_g \quad (2)$$

The experimental two-phase frictional pressure drop can be obtained from eq. (1) by subtracting the calculated gravitational pressure drop from the measured pressure drop:

$$\left(-\frac{dp}{dz}\right)_{f} = \Delta P_{tp} - \Delta P_g = \Delta P_{tp} - [\rho_G \alpha + \rho_L (1-\alpha)] g \sin\theta L \quad (3)$$

In eq. (3), L is the channel length, ρ_L is the liquid density, ρ_G is the gas density, g is the gravitational acceleration, the void fraction α is necessary to calculate gravitational pressure drop. Jones and Zuber [17] studied the void fraction in rectangular ducts, and proposed a correlation in view of drift flux model:

$$\frac{j_G}{\alpha} = C_0 j + (0.23 + 0.13\frac{s}{w})\sqrt{\Delta\rho g w / \rho_L} \quad (4)$$

where j_G and j_L denote the superficial gas and liquid velocity respectively, j is the mixture superficial velocity ($j = j_G + j_L$). C_0 is the distribution parameter, $\Delta\rho$ is the density difference of the two phase ($\Delta\rho = \rho_L - \rho_G$), s and w denote the height and width of the rectangular duct, respectively. Mishima and Ishii [18] suggested that the following equation for the distribution parameter was well correlated with the experiment data for the rectangular ducts:

$$C_0 = 1.35 - 0.35\sqrt{\rho_G / \rho_L} \quad (5)$$

Mishima and Hibiki [4] studied the void fraction in rectangular ducts for the 1.0 and 2.4 mm gaps, and found that the void fraction can be well predicted by drift flux model with the distribution parameter given by eq. (5).

For single-phase flow in narrow rectangular channel, the friction factor is expressed by the following equations:

$$\begin{cases} \lambda_l = C_l \mathrm{Re}^{-1} & \text{for laminar flow} \\ \lambda_t = C_t \mathrm{Re}^{-0.25} & \text{for turbulent flow} \end{cases} \quad (6)$$

where λ_l and λ_t are the friction factor for the laminar flow and turbulent flow, respectively. Re is the Reynolds number. Sadatomi *et al*. [19] proposed the following relationship between the coefficients C_l and C_t with the consideration of the channel geometry effect:

$$C_t = C_{t0}[(0.0154 C_l / C_{l0} - 0.012)^{1/3} + 0.85] \quad (7)$$

where C_{l0} and C_{t0} are taken from the friction factors for a smooth round tube, 64 and 0.3164, respectively. The friction factors for the laminar flow through the rectangular channels proposed by Hartnett and Kostic [20] is given as:

$$\lambda_l = C_l \mathrm{Re}^{-1} = 96(1 - 1.3553a + 1.9467a^2 - 1.7012a^3 + 0.9564a^4 - 0.2537a^5)\mathrm{Re}^{-1} \quad (8)$$

This simplified polynomial equation fits the exact analytical solution with an accuracy of ±0.05%, here, $a=s/w$. Mishima and Hibiki [4] also studied the single phase friction factor in rectangular ducts for 1.0, 2.45 and 5.00 mm gaps, and the results showed a very good agreement with equations above. For current case, Eq. (7) gives $C_t = 0.3369$ and Eq.(8) gives $C_l = 91.08$.

4. RESULTS AND DISCUSIONS

Test was first conducted to obtain the friction factor data of single-phase water flow in the rectangular test section, which was used to verify the applicability of the instrumentations and the reliability of Eq. (7) and Eq. (8). The experimental data of the friction factor are plotted in Figure **4**, which agree very well with the Eq. (7) and Eq. (8) for both the laminar and turbulent flow. The same results were also found from the work by Mishima and Hibiki [4].

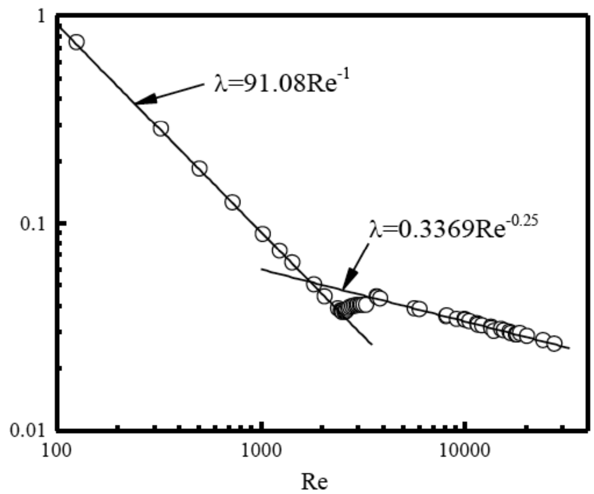

Figure 4: Friction factors for single-phase flow in rectangular duct.

4.1. Comparison with the Existing Correlations

Figure **5** shows a typical variation of the pressure gradients with the superficial gas velocity and the superficial liquid velocity. In general, as expected, the higher superficial velocity is, the greater the two-phase frictional pressure gradients are. 9 typical correlations, tabulated in Table **1**, were evaluated against the experimental results. Figure **6**(**a**)-(**e**) presents the comparison of experimental data with the calculated frictional pressure drop by the existing correlations. The abscissa denotes experimental pressure drop, while the ordinate is the calculated pressure drop by the existing correlations. The error band of ±30% is also shown by the solid lines in these figures.

Table **2** gives the mean absolute error and averaged error of the predictions calculated by these correlations. It is showed that the predicted pressure drop by the conventional correlations (Homogenous [21], Chisholm C coefficient [22], Chisholm B coefficient [23] and Friedel [8]) is lower than the experimental data. The reason that the correlations for conventional tubes fail to predict the pressure drop in small-channels is related to the different bubble behavior in narrow rectangular duct, coalesced bubbles are confined and elongated; the bubbles are restricted by the wall, resulting in greater pressure drop in narrow rectangular duct due to the additional friction. The correlations (Mishima and Hibiki [4], Tran and Chyu [24], Zhang and Hibiki [9], Sun and Mishima [10]) cannot be satisfactory with present experiments. Tran method over-predicted the experiment data, it may be due to the difference between the air-water and refrigerant boiling system. Lee-Lee correlation predicts the current experimental data better than the other correlations, but has lower values than the experimental data.

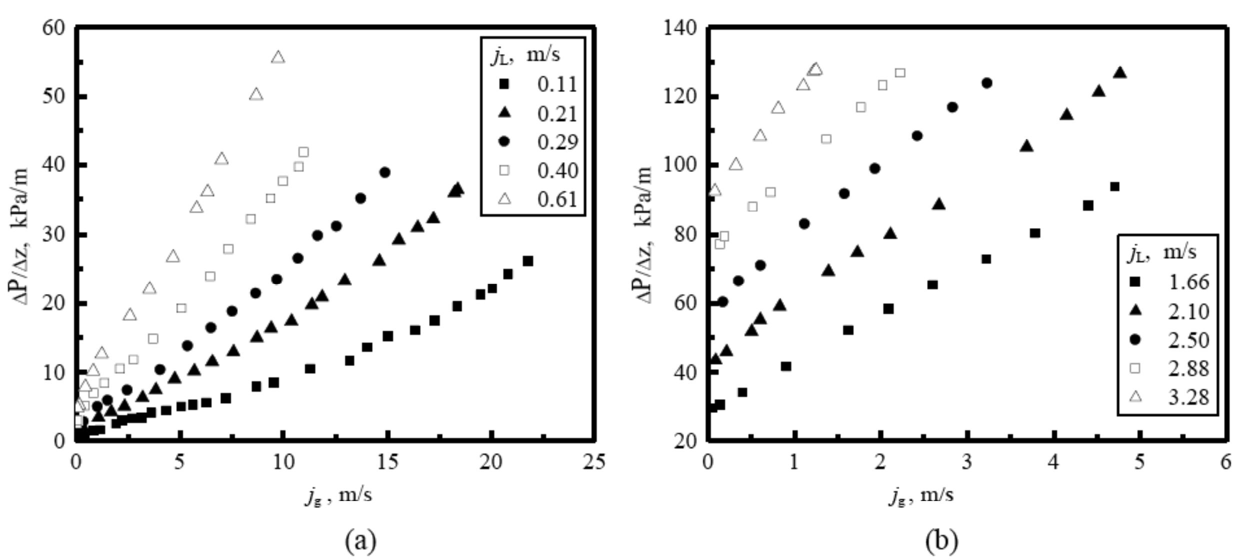

Figure 5: Variation of the pressure gradient with the superficial velocities.

Table 1: Typical Correlations[1]

<table>
<tr><th colspan="2">Existing Correlations</th></tr>
<tr><td>Homogeneous (McAdams,1954)</td><td>$\phi_{Lo}^2 = (\lambda / \lambda_{Lo})[1 + x(\rho_L / \rho_G - 1)]$， $1/\mu = x/\mu_G + (1-x)/\mu_L$</td></tr>
<tr><td>Chisholm C coefficient (1967)</td><td>$\phi_L^2 = 1 + C/X + 1/X^2$， $C = 5, 10, 12, 20$ for ll, tl, lt, tt (Liquid-gas)
l：laminar region，Re_L，Re_G<1000; t：turbulent region，Re_L，Re_G>2000;</td></tr>
<tr><td>Mishima and Hibiki (1992)</td><td>$\phi_L^2 = 1 + C/X + 1/X^2$， $C = 21[1 - \exp(-0.319 d_h)]$</td></tr>
<tr><td>Friedel (1979)</td><td>$\phi_{Lo}^2 = A_1 + 3.24 A_2 A_3 / (Fr_H^{0.045} We_H^{0.035})$， $A_1 = (1-x)^2 + x^2 (\rho_L / \rho_G)(f_{Go} / f_{Lo})$， $A_2 = x^{0.78}(1-x)^{0.24}$， $A_3 = (\rho_L / \rho_G)^{0.91} (\mu_G / \mu_L)^{0.19} (1 - \mu_G / \mu_L)^{0.7}$</td></tr>
<tr><td>Tran et al. (2000)</td><td>$\phi_{Lo}^2 = 1 + (4.3\Gamma^2 - 1)[N_{conf} x^{0.875}(1-x)^{0.875} + x^{1.75}]$， $N_{conf} = [\sigma / [g(\rho_f - \rho_g)]]^{0.5} / d_h$</td></tr>
<tr><td>Zhang and Hibiki (2006)</td><td>$\phi_L^2 = 1 + C/X + 1/X^2$， $C = 21[1 - \exp(-0.358/Lo)]$</td></tr>
<tr><td>Sun and Mishima (2009)</td><td>$\phi_L^2 = 1 + C/X + 1/X^2$
$\begin{cases} C = 26(1 + Re_L/1000)[1 - \exp(-0.153/(0.27 \times Lo + 0.8))] & \text{for } Re_L \le 2000 \\ C = 1.79(Re_G / Re_L)^{0.4}((1-x)/x)^{0.5} & \text{for } Re_L > 2000 \end{cases}$</td></tr>
<tr><td>Chisholm B coefficient (1973)</td><td>$\phi_{Lo}^2 = 1 + (\Gamma^2 - 1)[B x^{0.875}(1-x)^{0.875} + x^{1.75}]$ ， where $\Gamma^2 = (dp/dz)_{Go} / (dp/dz)_{Lo}$
<table>
<tr><th>Γ</th><th>G (kg/m²s)</th><th>B</th></tr>
<tr><td>≤9.5</td><td>≤500</td><td>4.8</td></tr>
<tr><td></td><td>500<<i>G</i><1900</td><td>2400/<i>G</i></td></tr>
<tr><td></td><td>≥1900</td><td>55/ $G^{0.5}$</td></tr>
<tr><td>9.5< Γ <28</td><td>≤600</td><td>520/($\Gamma G^{0.5}$)</td></tr>
<tr><td></td><td>>600</td><td>21/ Γ</td></tr>
<tr><td>≥28</td><td>—</td><td>15000/($\Gamma^2 G^{0.5}$)</td></tr>
</table></td></tr>
<tr><td>Lee and Lee (2001)</td><td>$\phi_L^2 = 1 + C/X + 1/X^2$， $C = f(\lambda, \psi, Re_{Lo}) = A \lambda^q \psi^r Re_{Lo}^s$
<table>
<tr><th colspan="2">pattern</th><th rowspan="2">A</th><th rowspan="2">q</th><th rowspan="2">r</th><th rowspan="2">s</th><th rowspan="2">Range of X</th><th rowspan="2">Range of Re_{Lo}</th></tr>
<tr><th>L</th><th>G</th></tr>
<tr><td>l</td><td>l</td><td>6.833×10^{-8}</td><td>-1.317</td><td>0.719</td><td>0.557</td><td>0.776-14.176</td><td>175-1480</td></tr>
<tr><td>l</td><td>t</td><td>6.185×10^{-2}</td><td>0</td><td>0</td><td>0.726</td><td>0.303-1.426</td><td>293-1506</td></tr>
<tr><td>t</td><td>l</td><td>3.627</td><td>0</td><td>0</td><td>0.174</td><td>3.276-79.415</td><td>2606-17642</td></tr>
<tr><td>t</td><td>t</td><td>0</td><td>0</td><td>0</td><td>0.451</td><td>1.309-14.781</td><td>2675-17757</td></tr>
</table>
l：laminar region，Re_L，Re_G<2000; t：turbulent region，Re_L，Re_G>2000;</td></tr>
</table>

[1]L：Liquid；G：Gas；

Table 2: Mean Deviation and Average Deviation Calculated for the Different Pressure Drop Correlations

Correlations	Homogeneous	C Coefficient	B Coefficient	Friedel	Miahima	Tran	Zhang-Hibiki	Sun	Lee-Lee
MAE (%)	32.05	26.00	36.46	52.08	33.61	84.26	42.13	39.94	24.81
Average error (%)	-27.24	-24.06	-36.46	-32.62	-27.27	71.27	-40.67	-39.02	-24.63

4.2. New Correlation Development

A new pressure drop correlation was developed on the basis of the Lockhart-Martinelli model [25] using a two parameter method [12]. The original concept of the Lockhart-Martinelli model came from the following equation:

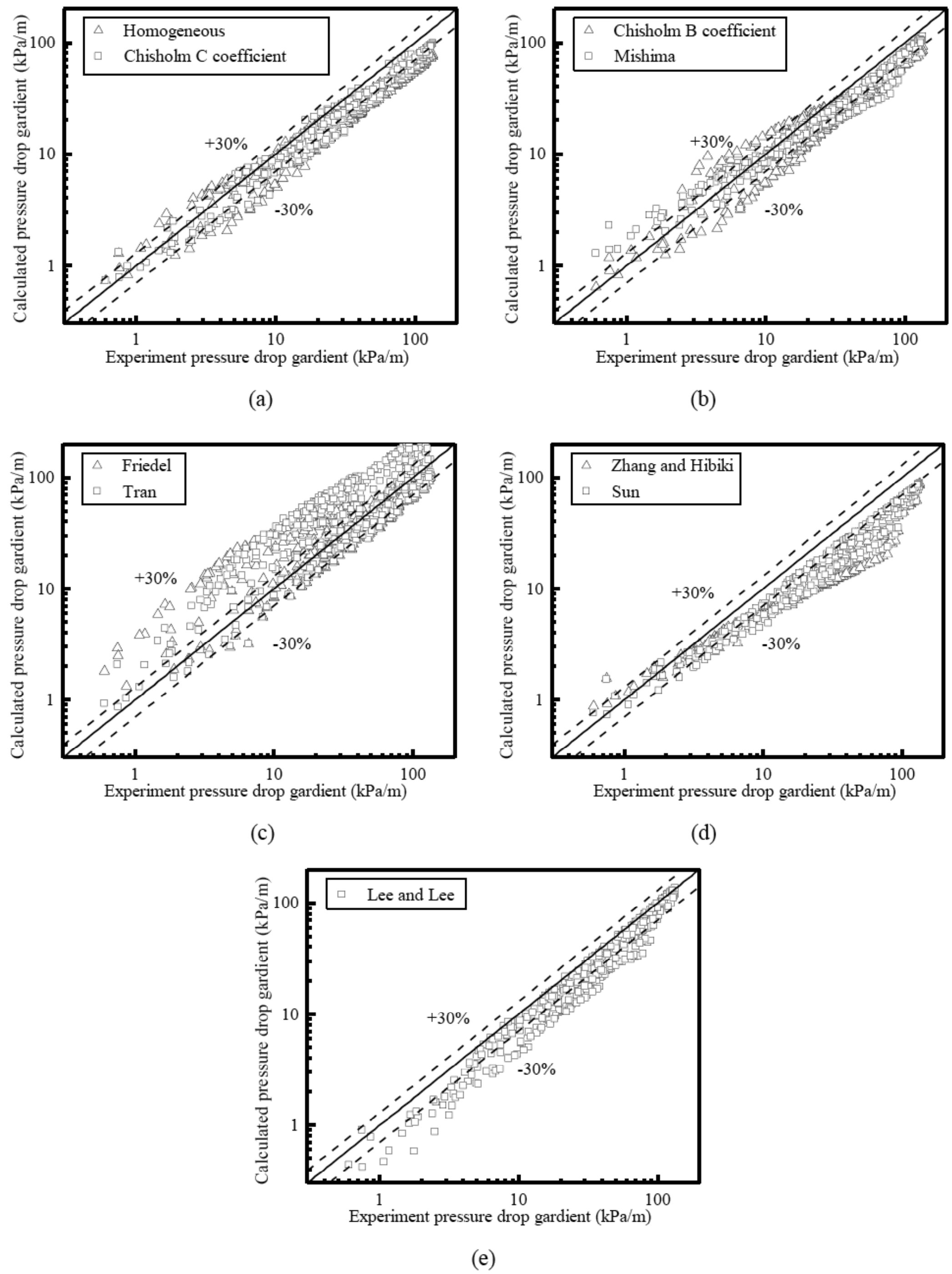

Figure 6: Comparison between experiment data points with the frictional pressure drop calculated by the existing correlations.

$$\left(-\frac{\mathrm{dp}}{\mathrm{dz}}F\right)_{\mathrm{tp}}=\left(-\frac{\mathrm{dp}}{\mathrm{dz}}F\right)_{\mathrm{L}}+C\left[\left(-\frac{\mathrm{dp}}{\mathrm{dz}}F\right)_{\mathrm{L}}\left(-\frac{\mathrm{dp}}{\mathrm{dz}}F\right)_{\mathrm{G}}\right]^{0.5}+\left(-\frac{\mathrm{dp}}{\mathrm{dz}}F\right)_{\mathrm{G}} \quad (9)$$

The two-phase pressure drop consists of three terms: the liquid phase pressure drop, the vapor phase pressure drop, and the interaction between the liquid phase and the vapor phase. The two-phase frictional multiplier based on the pressure gradient for liquid only flow, $\ddot{O}_{\mathrm{L}}^{2}$, is calculated by:

$$\ddot{O}_{\mathrm{L}}^{2}=\frac{\left(-\frac{\mathrm{dp}}{\mathrm{dz}}F\right)_{\mathrm{tp}}}{\left(-\frac{\mathrm{dp}}{\mathrm{dz}}F\right)_{\mathrm{L}}}=1+C\left[\frac{\left(-\frac{\mathrm{dp}}{\mathrm{dz}}F\right)_{\mathrm{G}}}{\left(-\frac{\mathrm{dp}}{\mathrm{dz}}F\right)_{\mathrm{L}}}\right]^{0.5}+\frac{\left(-\frac{\mathrm{dp}}{\mathrm{dz}}F\right)_{\mathrm{G}}}{\left(-\frac{\mathrm{dp}}{\mathrm{dz}}F\right)_{\mathrm{L}}}=1+\frac{C}{X}+\frac{1}{X^{2}} \quad (10)$$

Here, the parameter *C* in eq. (9) and (10) reflects the interaction between the phases, and is affected by many factors as the previous works showed. The

Martinelli parameter X is defined by the following equation:

$$X = \left[\frac{\left(-\frac{\mathrm{dp}}{\mathrm{dz}} F \right)_{\mathrm{L}}}{\left(-\frac{\mathrm{dp}}{\mathrm{dz}} F \right)_{\mathrm{G}}} \right]^{0.5} \tag{11}$$

Chisholm [22] gave the values of C according to different flow regimes of liquid-gas listed in Table **3**. The relationship between calculated $\ddot{O}_L^2$ by Chisholm model and the experimental data is shown in Figure **7**. The value of C is larger than Chisholm correlation; the values of C are closer in laminar-laminar, laminar-turbulent regimes and turbulent-laminar, turbulent-turbulent regimes. Table **4** gives the mean deviation and average deviation calculated for the Chisholm correlation in different regimes.

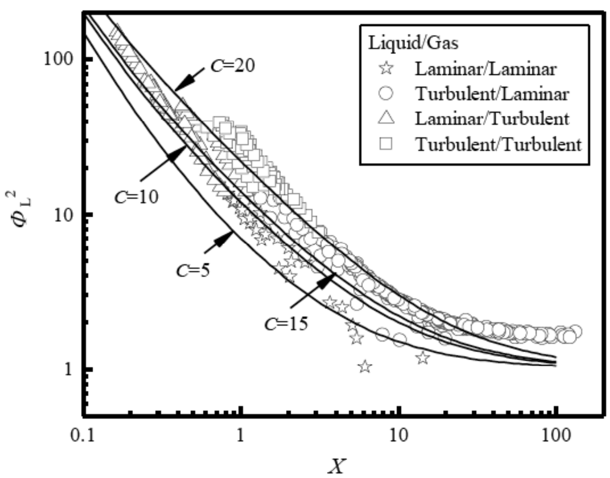

Figure 7: Predictions of Chisholm model versus present data.

Table **4** shows that the Chisholm correlation predicts the two-phase pressure drop better in laminar-turbulent and turbulent-turbulent regimes than in laminar-laminar and turbulent-laminar regimes. However, as seen in Figure **7** and Table **4**, eq. (10) with the constant values for C cannot predict the experimental data well; especially the case of large Martinelli parameter X. Figure **7** also shows that the liquid regime has a great influence on the parameter C. Here, three regions were divided according to the liquid Reynolds number, as shown in Figure **8**.

- Re_L<800: laminar zone.
- 800≤Re_L≤1400: transition zone.
- Re_L>1400: turbulent zone.

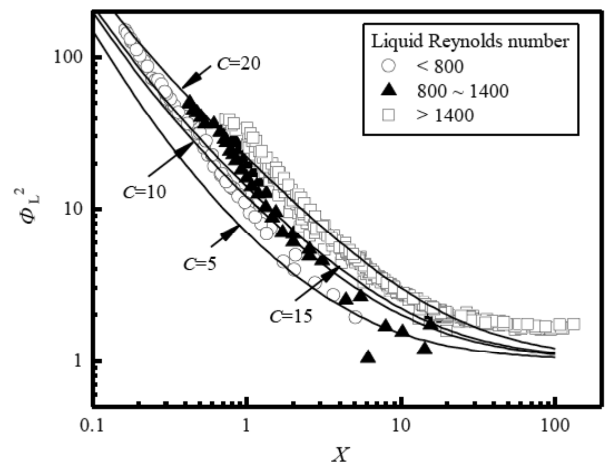

Figure 8: Relationship between $\ddot{O}_L^2$ and X divided according to the liquid Reyonlds number.

Table 3: Parameter C (Chisholm, 1967)

Flow Regime				
Liquid -Gas	Laminar -Laminar	Turbulent -Laminar	Laminar -Turbulent	Turbulent -Turbulent
Re_L Re_G	<1000 <1000	>2000 <1000	<1000 >2000	>2000 >2000
C	5	10	12	20

Table 4: Mean Deviation and Average Deviation Calculated for the Chisholm Correlation in Different Flow Regimes

Flow regime				
Liquid -Gas	Laminar -Laminar	Turbulent -Laminar	Laminar -Turbulent	Turbulent -Turbulent
MAE (%)	30.52	29.99	16.79	16.04
Average error (%)	-22.54	-29.44	-10.91	-14.40

As seen in Figure **8**, the Chisholm correlation cannot predict the present data well. Sun and Mishima [10] found that the index m in eq. (10) is not 1. And based on the statistical analysis, the Lockhart-Martinelli correlation can also be modified using a two parameter method as eq. (12).

$$\ddot{O}_{\mathrm{L}}^2 = 1 + \frac{C}{X^{\mathrm{m}}} + \frac{1}{X^2} \tag{12}$$

where m=1.4. Combining his conclusion and our experimental results, above-mentioned formula can be given as:

$$\ddot{O}_{\mathrm{L}}^2 = 1 + \frac{8.5}{X^{1.4}} + \frac{1}{X^2} \text{ Laminar zone} \tag{13}$$

$$\ddot{O}_{\mathrm{L}}^2 = 1 + \frac{14.5}{X^{1.4}} + \frac{1}{X^2} \text{ Transition zone} \tag{14}$$

For the turbulent region, especially when X>10, analysis results show that the value of C strongly depends on the ratio of Re_L to Re_G as Sun and Mishima [10] has stated in the turbulent region, which is clearly shown in Figure **9**.

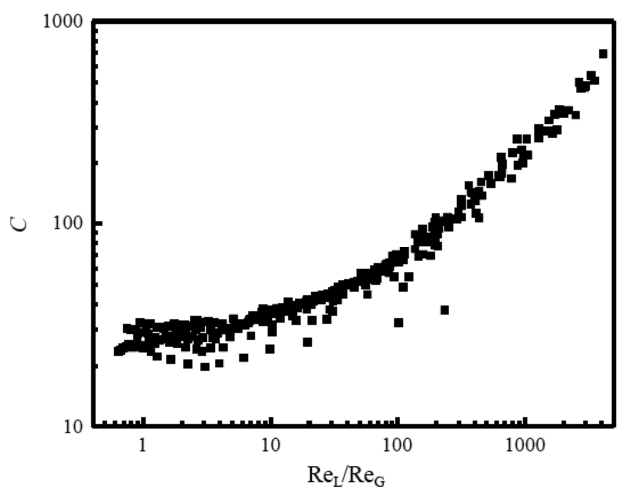

Figure 9: Relationship between C and $\mathrm{Re_L/Re_G}$.

Based on the statistical analysis of 426 experimental data points, the parameter C in eq. (12) is developed as a function of $\mathrm{Re_L/Re_G}$:

$$\ddot{O}_{\mathrm{L}}^2 = 1 + \frac{C}{X^{1.4}} + \frac{1}{X^2} \tag{15}$$

$$C = 1.22\left(\mathrm{Re_L} / \mathrm{Re_G}\right)^{0.74} + 27.5 \tag{16}$$

The two-phase pressure drop in the above three regions can be calculated by Eqs. (13), (14) and (16), respectively. Figure **10** illustrates the comparison between the present experimental data with the modified correlation. The predicted pressure drop agrees well with the experimental data with a mean deviation of 7.2%.

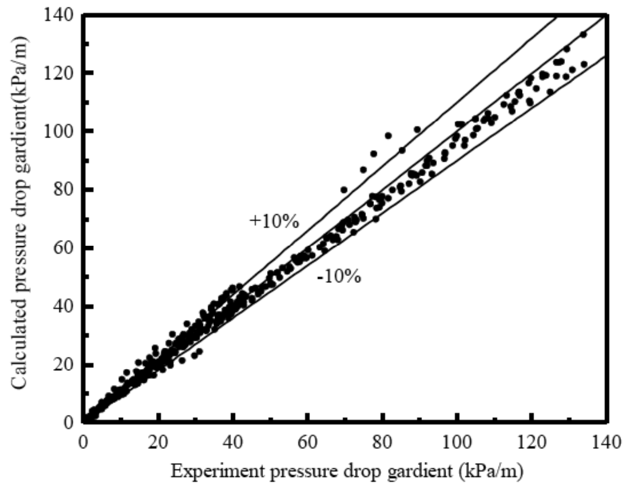

Figure 10: Comparison between experimental data and the frictional pressure drop calculated by the modified correlations.

CONCLUSIONS

In this study, two-phase pressure drop of air-water in a vertical narrow rectangular channel was performed. Based on the foregoing discussions, the following summaries are concluded:

1. The conventional methods for calculation of two-phase flow pressure drop cannot well predict the experimental results of the narrow rectangular channel.

2. The correlations based on the rectangular channels also cannot be satisfactory with the experiments. Tran method over-predicted the experiment data; Lee-Lee correlation gives a better agreement with the experimental data, but still has lower values compared with the experimental data.

3. The two-phase flow is divided into three regions according to the liquid Reynolds number, laminar, transition and turbulent regimes. Modified correlations for calculating two-phase flow pressure drop were proposed according to the three regions, and have a good agreement with the experimental data.

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