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Two-Phase Pressure Drop Calculations in Small Diameter Inclined Tubes

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Abstract

Effect of inclination on two-phase frictional pressure drop was investigated in small diameter circular tubes with inner diameters of 4.0, 6.0, 8.0 and 10.0 mm using air and water. Pressure drop was measured and compared with various existing models commonly used for macro and micro channels such as homogeneous, Lockhart-Martinelli, Chisholm, Friedel, Mishma Hibiki, and Zang Mishma. It was found that existing correlations are inadequate in predicting pressure drop for small diameter inclined tubes. The void fraction is calculated using a general void fraction correlation in two-phase flow for various pipe orientations. Based on analysis of present experimental frictional pressure drop data, a correlation is proposed for predicting Chisholm parameter "C" in small diameter inclined tubes. There was a significant ordering of pressure drop data with respect to Reynolds number, Webber number and Bond number for each diameter.

Keywords: *air-water, correlation, pressure drop, small diameter, two-phase flow.*

1 Introduction

Two-phase pressure drop estimation plays an important role in the design of process control systems, steam power plants, refrigeration, air conditioning system, and nuclear power plant system. Small diameter tubes are used in compact heat exchangers. Due to the complexity of the problem, in spite of several decades of research the approach is still primarily empirical. There are a number of correlations reported in the literature which are used for calculation of pressure drop in macro, mini and micro channels. These are based on experiments conducted in laboratory, where data can be obtained systematically and accurately.

The fictional pressure drop can be determined by different models or correlations for macro and mini, micro channels. The homogeneous correlation that makes the analysis of two-phase easier; this ideal-fluid obeys the usual equation of a single-phase fluid and is characterized by suitably averaged properties [1]. In Martinelli model [2] the Martinelli parameter, *x*, is the combination of the inertia and viscous forces of both phases. It is one of the most dominant parameters to correlate two-phase friction pressure gradient for small diameter tubes. The Friedel [3] and Chisholm [4] correlation for two-phase frictional pressure drop was specially developed for conventional channels. Mishma and Hibiki [5] predicted frictional pressure drop for air-water flow in vertical capillary tubes of inner diameters in the range of 1-4mm. The frictional pressure drop was predicted by Chisholm's equation [4] with modified Chisholm parameter C as a function of inner diameter. The Chisholm's parameter C [4] was correlated with the hydraulic diameter of channel as

$$C = 21[1 - \exp(-0.319 D_h)] \tag{1}$$

Chen et al. [6] developed an empirical correlation based on the homogeneous and Friedel [3] model. It was recognized by the research of Chen et.al. [6],Garimella [7], Triplett [8]that surface tension force plays important role for tubes of diameters less than 10mm.

The two-phase flow phenomenon in vertical pipes is of prime interest because of the significant influence of the interaction of gravity, buoyancy, and inertia forces on the individual phases. It has been observed and experimentally verified that two-phase flow parameters such as flow patterns, interaction of forces, and void fraction are affected by the change in flow direction from vertical upward to vertical downward. [11].

Afshin J. Ghajar and Clement. C. Tang [12] compared the performance of 54 void fraction correlations based on unbiased experimental data set of 3385 data points. They developed a general correlation regardless of flow pattern, gas-liquid combination and pipe inclination angle. This correlation based on drift flow model.

In inclined two-phase flow the most extensive study has been reported by Beggs and Brill [13]. Mukherjee and Brill [14], The Beggs and Brill method remains perhaps the best known. The Beggs and Brill correlation is based on data they gathered in 90 ft long pipes with internal diameters 1 and 1.5 in. These pipes were inclined at various angles between 0 to 90 degrees in both upward and downward directions.

M.Venkatesan et.al, [15] studied two-phase flow pattern and pressure drop experimentally using air-water mixtures. The different tube diameters used ranging from 0.6-3.4 mm. After the comparison of experimental data with existing correlations; they proposed new correlation by modification of Chisholm parameter C.

$$C = 4(We_l)^{0.3}\left(\frac{Re_G}{Re_l}\right)^{0.5} \text{ for Bo> 1} \tag{2}$$

$$C = 2(We_l)^{0.5}\left(\frac{Re_G}{Re_l}\right)^{0.5} \text{ for Bo<1} \tag{3}$$

A very few pressure drop correlations are available for calculation of two-phase pressure drop in inclined tubes in both upward and downward directions.

2 Experimentations

2.1 Experimental set-up

A schematic diagram of the experimental set-up is shown in Figure 1. The test facility was designed for several future investigations to study two-phase pressure drop in micro-channels, mini-channels, sudden contraction, sudden expansion etc. The arrangement was made for mounting the test sections at different orientations. An explicit slot is provided on the cardboard to fix the test section at different required orientation ranging from 0^0 to + 90^0 and -90^0

Water from the water tank is pumped to the test section by centrifugal pump. The water flow rate is regulated with the help of hand shut off valve and bypass valve. Similarly, the air flow rate is regulated through set of hand shut off valve and by pass valve.

Air and water are mixed in the mixing chamber. This mixture of air and water from the mixing chamber passes through the test section. Air-water mixture coming out from the test-section collected in the water tank. In the water tank air gets separated and the water is recirculated.

In this experiment, four different diameters test sections were used. These are made up of transparent acrylic material with circular cross section, with a total length 600 mm and internal diameters of 4.0, 6.0, 8.0 and 10.0 mm. The total length of test section is divided into the three segments: 1. entrance segment of 150 mm length used for stabilization of flow after the mixing chamber. 2. Measuring segment of 400 mm length was used for measurement of pressure drop 3. Outlet segment is of 50 mm length to avoid the back pressure effect on the measurement of pressure drop.

The pressure drop of the air-water mixture is measured by a differential pressure transducer. The measuring range of this differential pressure transducer is 0-1 bar. Pressure transducer of range 0-2.5 bar is used for measurement of the inlet static pressure. The least count of both differential transducers are 0.001bar. The following flow parameters were measured: flow rates of air and water, pressure drop and temperature recorded by a data acquisition system in the test section. Two rotameters were used in this experiment to measure the mass flow rate. One was used for water flow line having a range 0-3 LPM while the other was used in the air line having a range 0-100 LPM. A pressure gauge was located just before the inlet to the mixing chamber (range of 0-150 lb/in²).This is used to measure the static pressure of air for calculation of density. [16]

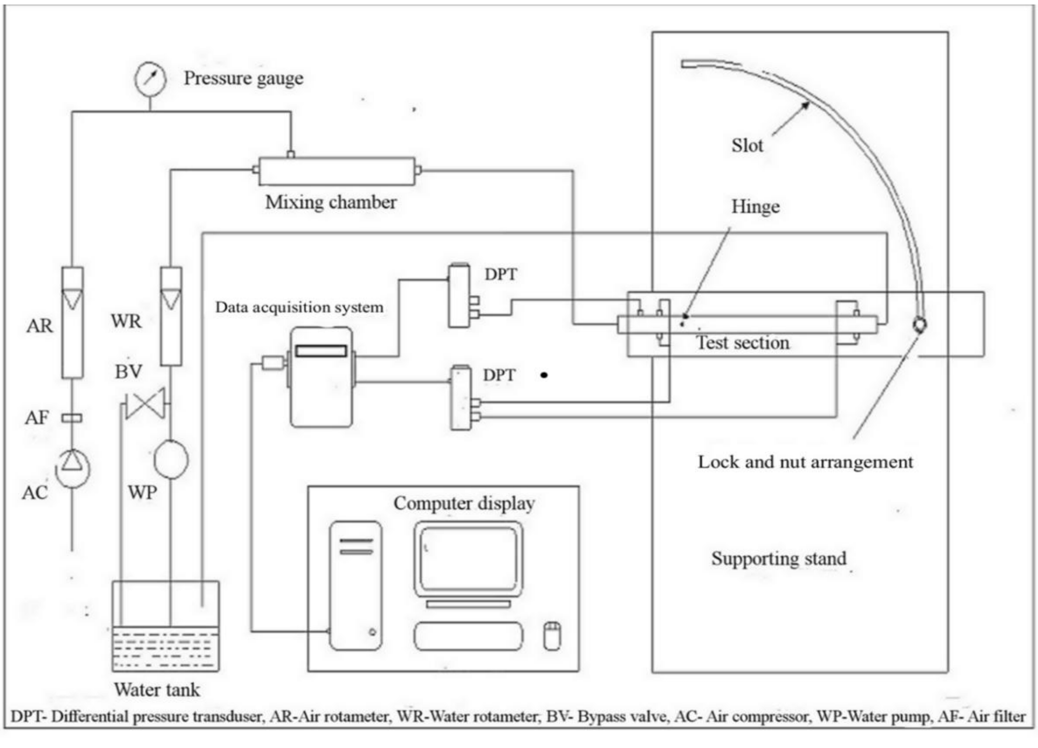

Figure 1. Schematic diagram of experimental setup

2.2 Mixing chamber

The design of the mixing chamber is tricky. In order to avoid the back pressure of air and water after mixing on measuring instruments, design of mixing chamber is very much important. The mixing chamber is specially designed as shown in figure 2. The water enters the mixing chamber at the center and air enters at 90 degree angle from the top. Two circular steel strips of 12 mm width, 27.8 mm outside diameter are joined together with a center hole of 16 mm. These strips are fixed inside a GI pipe of internal diameter 27.8 mm and length 400 mm. One of the circular strips has 8 holes of 2.5 mm drilled at equal distance and these holes are internally connected to each other with small channel through which air is supplied. The air and water flows get mixed and flows smoothly in chamber in the same direction without creating any back pressure effect on the measuring device. [16]

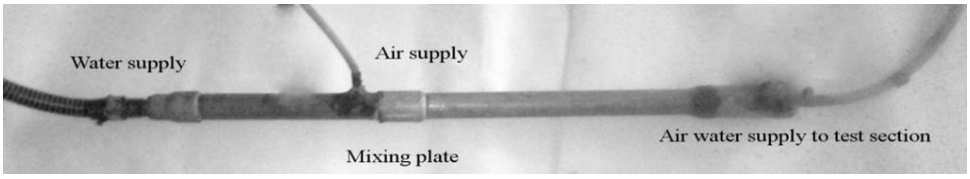

Figure 2. Mixing chamber

2.3 Bench-marking of the experimental set-up

Single-phase pressure drop tests were conducted to validate experimental set-up and instrumentation. Experiments were conducted with 4.0 mm internal diameter and 400 mm length test section Water was used as working fluid. The experimental pressure drop for water flow was recorded. Figure 3 shows the comparison of the experimental friction factor *f* with Blasius correlation predicted values. It is observed that experimental values are in good agreement with Blasius correlation prediction .The error band was ±5 percent.

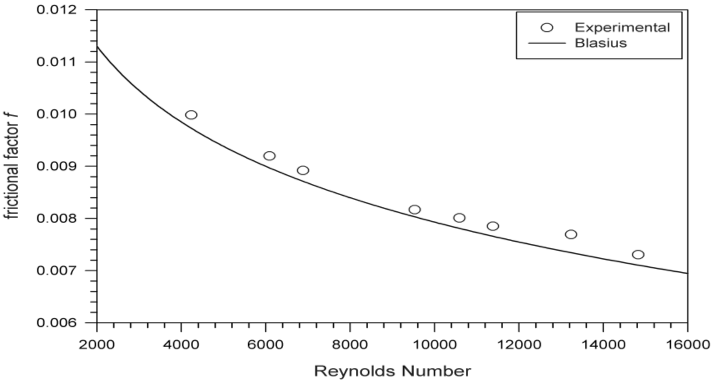

Figure 3.Comparison of experimental single-phase friction factor with Blasius correlation

3 Two-phase Pressure Drop

3.1 Pressure drop models for data reduction

Readings of total pressure drop at 30^0 orientations, were recorded in steady state. Total pressure drop of a fluid is due to the variation in kinetic and potential energy and friction, so that the pressure drop is the sum of the static pressure drop (elevation head), the momentum pressure drop (acceleration) and frictional pressure drop.

$$\left(\frac{dP}{dz}\right)_T = \left(\frac{dP}{dz}\right)_s + \left(\frac{dP}{dz}\right)_m + \left(\frac{dP}{dz}\right)_f \tag{4}$$

As test sections are circular hence the momentum pressure drop is zero.

$$\left(\frac{dP}{dz}\right)_m = 0 \tag{5}$$

$$\left(\frac{dP}{dz}\right)_T = \left(\frac{dP}{dz}\right)_S + \left(\frac{dP}{dz}\right)_f \tag{6}$$

The static pressure drop can be calculated

$$\left(\frac{dP}{dz}\right)_s = \rho_m g H \sin\theta \tag{7}$$

Where ρ_m is the mixture density

$$\rho_m = \varepsilon\rho_G + (1-\varepsilon)\rho_L \tag{8}$$

The void fraction was calculated using Afshin J. Ghajar et al. [12], a general correlation in two-phase flow for various pipe orientations.

$$\alpha = \frac{V_{sg}}{C_o\left(V_{sg} + V_{sl}\right) + u_{gm}} \tag{9}$$

$$C_o = \frac{v_{sg}}{v_{sg} + v_{sl}}\left[1 + \left(v_{sl}/v_{sg}\right)^{\left(\rho_g/\rho_l\right)^{0.1}}\right] \tag{10}$$

$$u_{gm} = 2.9\left(1.22 + 1.22\sin\theta\right)^{\frac{P_{atm}}{P_{sys}}}\left[\frac{gD\sigma\left(1+\cos\theta\right)\left(\rho_l - \rho_g\right)}{\rho_l^2}\right] \tag{11}$$

Where subscripts *l* and *g* refer to the liquid phase and gas phase and C_0 = two-phase distribution coefficient, D=tube diameter, g = gravitational acceleration, m/s^2 P_{atm} = atmosphere pressure, N/m^2, P_{sys} = system pressure, N/m^2, u_{gm} =gas drift velocity, m/s V_{sg} = superficial gas velocity, m/s, V_{sl} = superficial liquid velocity, m/s, α = void fraction, ρ = density, kg/m^3, σ = surface tension, N/m, θ = inclination angle, rad

$$\Delta P_{TP} + \Delta P_{static} = \Delta P_{friction} \quad \text{(Two-phase flow in upward inclined pipes)} \quad (12)$$

Experimental frictional pressure drop calculated using equation (12), and compared with the existing correlations used for macaro and mini/micro channels homogenous model, Chisholm modified Lockhart Martinelli, Friedel, Mishma and Hibiki, Zang and Mishma and Wei Li and Zan.

3.2 Comparison of experimental pressure drop data with existing correlations

The Experimental data for all four small diameter tubes were compared with four state-of-art correlations for predicting two-phase frictional pressure drop in macro channels: homogenous model, Lockhart Martinelli, Friedel, modified Friedel correlation (Chen et al.).

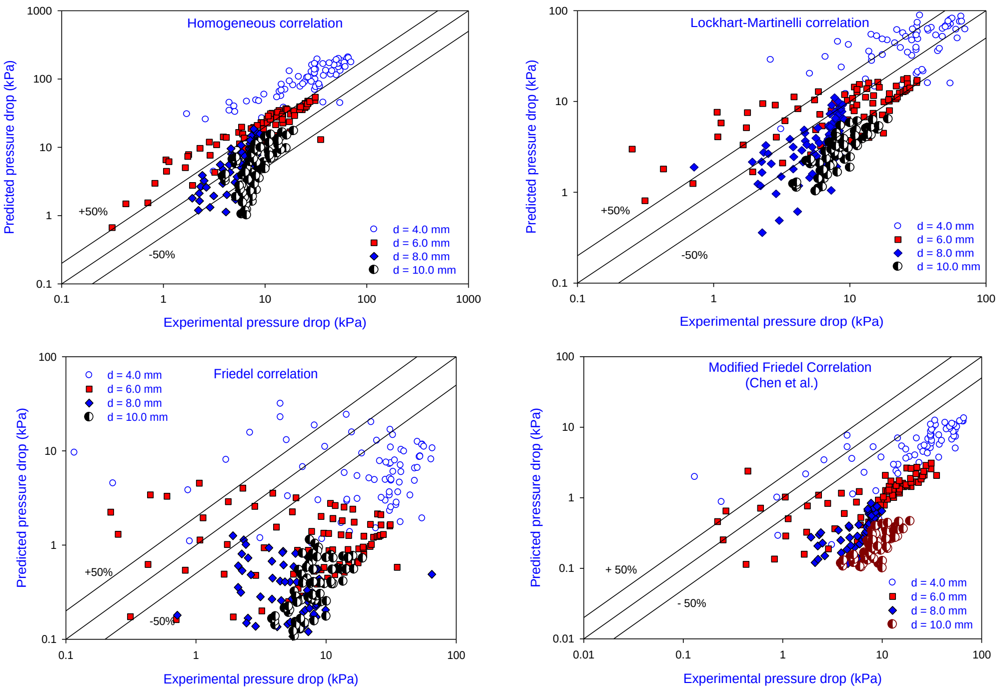

Figure 3. Comparison of experimental pressure drop with existing macro channel correlations

These correlations were developed specially for large tube diameters >8 mm. A careful review of the frictional two-phase flow pressure drop comparison between measured data and the four large-tube correlations led to the conclusions below. There is general agreement in the literature pertaining to two-phase flow in minichannels that surface tension has increasing effect on the flow behavior and pressure drop as channel diameter decreases [17].Homogeneous and Lockhart-Martinelli correlations over predicts frictional pressure drop of 4.0 and 6.0 mm diameter tubes where as Friedel correlation not shown any trend and modified Friedel (Chen) correlation under estimate these values. Predictions by homogeneous model for 8.0 and 10.0 mm diameter tube were more satisfactory shown within 50% error band, where the predictions of other correlations were quite poor.

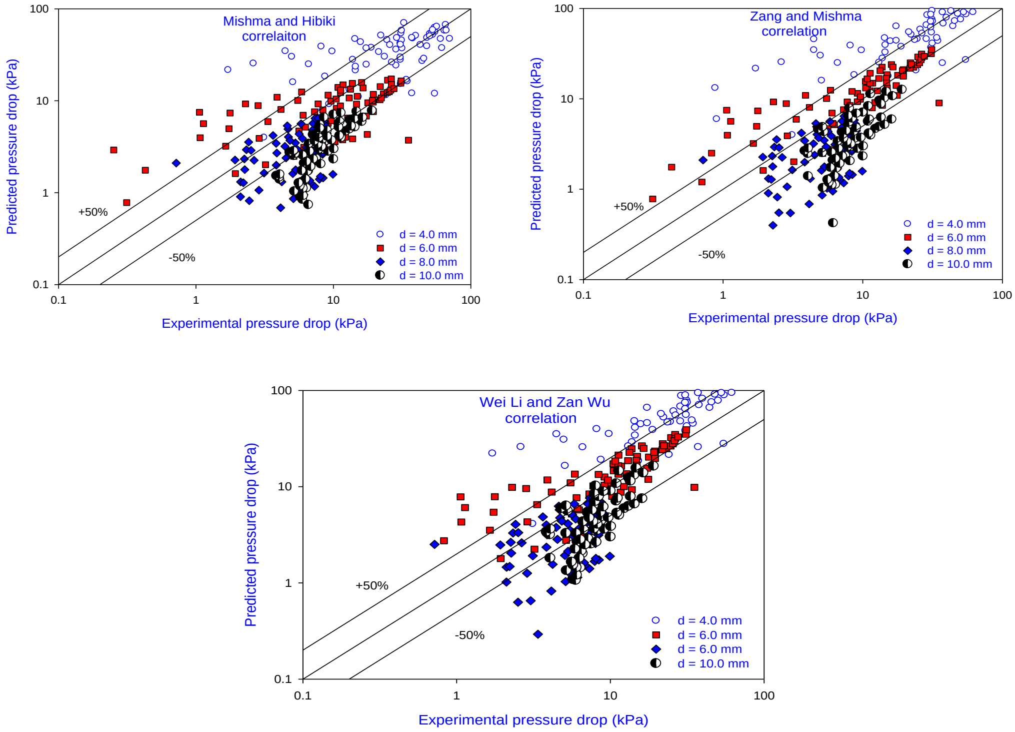

Figure 4. Comparison of experimental pressure drop with mini/micro channel correlations

It can be seen from the comparison presented in the figure 4 that the Mishma and Hibiki, Zang and Mishma,and Wei li and Zan Wu correlations over predicts the experimental data of 4.0 mm diameter tube and under estimate the 10.0 mm diameter tube. All these correlations are developed by modification of Chisholm parameter C. Frictional pressure drop data of 8.0 and 10.0 mm diameter tubes comparatively in satisfactory region.

Table 1. Statistics of the evaluated correlation for friction pressure drop data.

Diameter (mm)	4.00		6.00		8.00		10.0	
correlation	e_R	σ_N	e_R	σ_N	e_R	σ_N	e_R	σ_N
Homogenous	620.96	1826.35	309.57	1363.91	51.92	79.46	42.63	50.54
Lockhart Martinelli	3100.54	24346.00	236.38	856.37	45.48	40.09	57.35	21.03
Friedel	234.59	965.27	111.26	125.69	90.82	11.05	95.26	2.92
Modified Friedel (Chen)	662.36	3403.14	90.51	43.09	94.91	3.17	97.90	1.0
Mishima and Hibiki	1857.93	10267.3	204.01	619.39	50.48	30.46	62.34	15.78
Zhang and Mishima	3102.00	23370.7	224.90	868.45	50.49	28.98	78.00	32.93
Wei Li and Zan Wu	6317.4	36112.52	249.75	956.16	45.35	33.90	46.06	26.15

Mean or average deviation $e_R = \frac{1}{N_p}\sum_{i=1}^{Np}\frac{\left(\frac{dp}{dz}_{\text{Predicted}} - \frac{dp}{dz}_{\text{Expt}}\right)}{\frac{dp}{dz}_{\text{expt.}}}\times.100$ Standard deviation $\sigma_N = \sqrt{\frac{\sum_{I=1}^{Np}(e_i - e_R)^2}{Np-1}}$

4 Proposed new correlation

Lockhart-Martinelli [2] defined a two-phase friction multiplier to relate the two-phase pressure gradient to the single-phase pressure gradient for liquid flow. They defined the Lockhart-Martinelli parameter, X^2, as the ratio of the single-phase liquid and gas pressure gradients, and graphically represented the relationship between the friction multiplier, ϕ^2, and Lockhart-Martinelli parameter *x*. Chisholm and Laird[10] related the friction multiplier to the Lockhart-Martinelli parameter through the simple expression that depends upon the coefficient C. The constants of C =5,10,12 and 20 represents combinations of flow pattern in laminar and turbulent flow conditions for gas and liquid phases.

$$\varphi_l^2 = 1 + \frac{C}{\chi} + \frac{1}{\chi^2} \qquad (13)$$

Figure 5 shows the two-phase friction multiplier φ_l^2 data plotted against the Lockhart-Martinelli parameter *x* for 4.0, 6.0, 8.0 and 10.0 mm diameter tubes at 30^0 upward orientation. The experimental value of C for 4.0 and 6.0 mm for different flow regimes are underperidicts the theoretical value.

Theoretically, there are four forces related to two-phase flow in channels: gravitational, inertia, viscous, and surface-tension forces[15]. The basic reason for the difference between conventional channels and micro/minichannels is the relative significance other four forces, which are included in our calculation in the dimensionless numbers: the Bond number and the Reynolds number. On one hand the comparison of the channel dimension and the nominal bubble size can be expressed in terms of the Bond number. The Bond number is the measure of the importance of the body forces (almost always gravitational) compared to surface-tension forces. A high Bond number indicates that the system is relatively unaffected by surface tension effect: a low Bond number indicates that the surface tension dominates. As channel hydraulic diameter becomes smaller, the bubbles are squeezed in the flow channel and surface tension gradually dominates the flow. On other hand, the Reynolds number gives a measure of ratio of inertia force to viscous force and consequently quantifies the relative importance of these two types of forces for given flow conditions. Reynolds number plays important roles in characterizing different flow regimes, such as laminar and turbulent flow: laminar flow occurs at low Reynolds numbers where viscous force are dominant, while turbulent flow occurs at high Reynolds numbers and is dominated by inertia forces.[9]. Lee and Lee [10] also proposed a correlation for modification of the parameter C in the Lockhart and Martinelli type correlation.

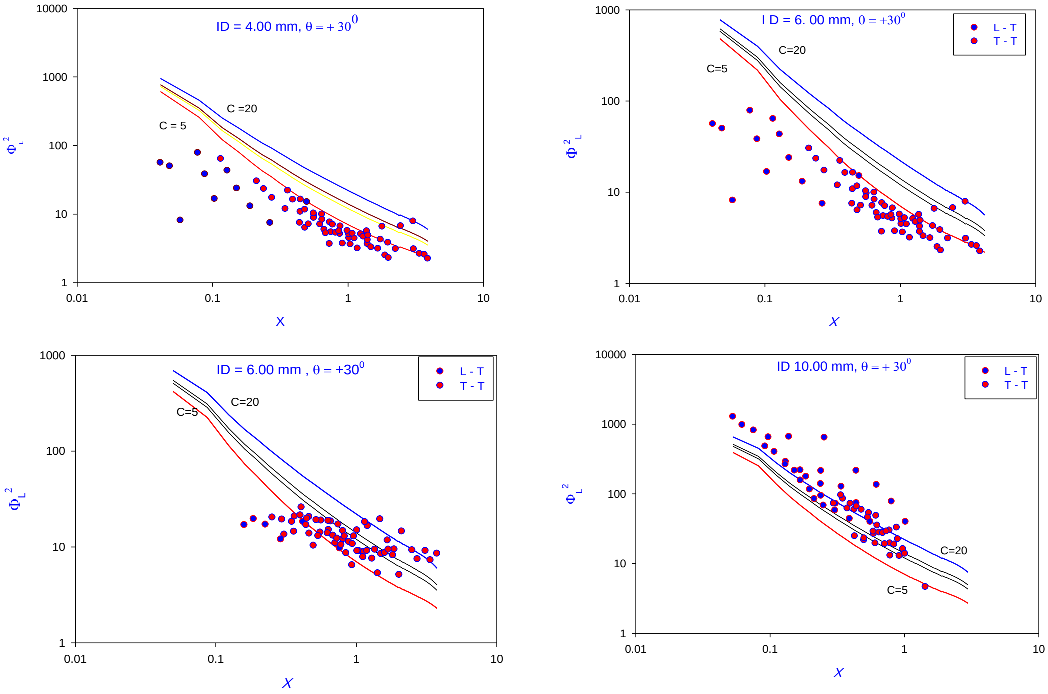

Figure5. Comparison of the calculated correction factor φ_l^2 (C=5, C=10, C=12 and C=20 - solid lines) and the experimental correction factor φ_l^2 versus Martinelli parameter *x*: L-T laminar flow of water- turbulent flow of air; T-T turbulent flow water-turbulent flow of air.

In an attempt to develop an improved correlation based on the relevant scaling effects observed in this study and adoption from previous studies, a modified form of Eq. (13) has been developed to better predict the experimental data.

$$C = 250(\mathrm{We})^{-0.70} \times (\mathrm{Bo})^{0.96} \times (\mathrm{Re}_L)^{0.21} \tag{14}$$

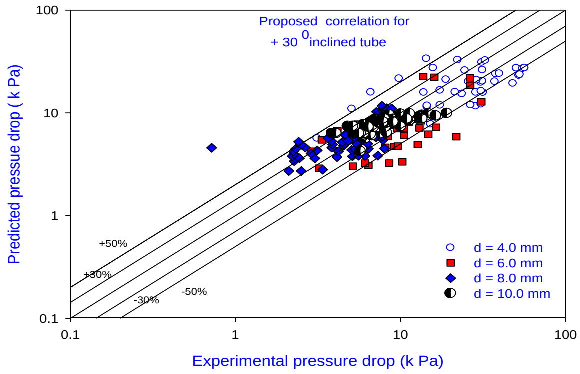

Figure 6. Comparison of experimental pressure drop with proposed correlation.

As mentioned above, there is influence of various parameters on value of constant C. The test section dimensions used in present study lies at extreme end of minichannels and beginning of macrochnnels. Considering above discussed issues, it is decided to modify Chisholm correction factor of two-phase multipliers.

Reynolds number show significance of inertial force and viscous force as the mass flux of liquid and air increases due this there is interaction between the fluids and inertial force dominate. This effect increase in frictional pressure drop as decrease in diameter of the tubes.

Figure 6 presents the comparison of experimental pressure drop with predicted pressure drop using proposed correlation. Most of the data points of 4.0, 6.0, 8.0 and 10.0 mm internal diameter tubes are within 50% band.

5 Conclusion

Air-water mixture concurrently flowing through small diameter 30^0 inclined tubes presents different flow characteristics than those exhibits in single phase and two-phase with large diameter tubes. Based on experimental findings from this research as well as exiting literature, following conclusions are presented.

1. The void fraction was calculated using Afshin J. Ghajar et al. [12], a general correlation in two-phase flow for various pipe orientations.
2. A very extensive comparison of most of the pressure drop correlations available in open literature was made against the 320 experimental data points for upward 30^0 inclined small diameter tubes.
3. The tube diameters used in this research study are lies in between extreme of minichannels and beginning of macochannels hence four

macochannel and three mini/microchannel correlations are used for comparison of frictional pressure drop.

4. After comparison with these frictional pressure drop correlations with experimental pressure drop data points it was found that none of existing correlation shows the satisfactory results.
5. Modification in Chisholm parameter C has been suggested in proposed correlation which includes effects of different parameters such as surface tension, mass flux, and diameter of tubes.

Nomenclature

Bo	Bond number, $g\cdot(\rho_l-\rho_g)\cdot D^2/\sigma$
C	constant in Chisholm correlation
E	variable in Friedel correlation
F	variable in Friedel correlation
H	variable in Friedel correlation
F	friction factor
Fr	Froude number, $G^2/(\cdot g\cdot D\cdot\rho_m^2\cdot)$
G	mass flux $(kg/m^2\cdot s)$
N	total number of data points
ΔP	pressure drop (kPa)
We	Weber number, $G^2D/\sigma\cdot\rho_m$
x	mass fraction, $\frac{\text{mass of air}}{\text{mass of air}+\text{mass of water}}$
χ	Martinelli parameter
Greek symbols	
ϕ_l^2	two-phase friction multiplier for liquid flowing alone
μ	dynamic viscosity, $(N\cdot s/m^2)$
ρ	density (kg/m^3)
ρ_m	mixture density, (kg/m^3)
σ	surface tension of liquid (N/m)
Ω	Chen correlation factor
Subscripts	
g	gas phase only
l	liquid phase only
TP	Two-phase

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