AN EXPERIMENTAL STUDY ON TWO-PHASE PRESSURE DROP IN SMALL DIAMETER HORIZONTAL, DOWNWARD INCLINED, AND VERTICAL TUBES

by

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An experimental study of two-phase pressure drop in small diameter tubes orientated horizontally, vertically and at two other downward inclinations of $\theta = 30°$ and $\theta = 60°$ is described in this paper. Acrylic transparent tubes of internal diameters 4.0, 6.0, and 8.0 mm with lengths of 400 mm were used as the test section. Air-water mixture was used as the working fluid. Two-phase pressure drop was measured and compared with the existing correlations. These correlations are commonly used for calculation of pressure drop in macro and mini-microchannels. It is observed that the existing correlations are inadequate in predicting the two-phase pressure drop in small diameter tubes. Based on the experimental data, a new correlation has been proposed for predicting the two-phase pressure drop. This correlation is developed by modification of Chisholm parameter C by incorporating different parameters. It was found that the proposed correlation predicted two-phase pressure drop at satisfactory level.

Key words: *two-phase pressure drop, small diameter, inclined tubes*

Introduction

Two-phase flow phenomenon is observed in a number of industrial applications such as in the fields of energy, petroleum, refrigeration and air conditioning, nuclear and chemical systems. Compact heat exchangers are being widely used in the refrigeration and air conditioning, chemical processing systems, and high power electronic device cooling systems. Compactness reduces the amount of charge of the fluid, which has also a direct positive impact on safety and environment. However, the negative point is possibly a higher pressure drop related to the flow in mini-micro channel [1]. During recent years, the design of residential air conditioners has employed smaller diameter tube (6.35-9.53 mm) in order to improve the airside performance and to reduce the refrigerant charge into the system and more recently the air-conditioning manufactures are implementing the related application by use of 4-5 mm diameter tubes [2].

Two-phase pressure drop in conventional channels has been calculated using three well-known correlations by Lockhart and Martinelli [3], Chisholm [4], and Friedel [5]. The

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Lockhart-Martinelli correlation [3] was based on adiabatic flows of air and benzene, kerosene, water and various oils passing through 1.5-26 mm pipes and the pressure drops were correlated based on whether the individual liquid and gas phases were considered to be in laminar or turbulent flow. Conrad *et al*. [6] measured the frictional pressure loss for air-water flows in vertical capillary tubes with a diameter ranges from 1-4 mm. The results from their study were compared with the Lockhart-Martinelli correlation and reported frictional pressure drop by modification of Chisholm's parameter, *C*, as a function of inner diameter. Zhang and Webb [7] measured adiabatic two-phase flow pressure drops for R-134a, R-22, and R-404a in a multi-port extruded aluminum tube with hydraulic diameters of 6.25 mm and 3.25 mm, respectively. They developed new correlation for measurement of two-phase pressure drop in small diameter tubes. Chen *et al.* [8] developed an empirical correlation for small-diameter tubes based on modification of homogenous and Friedel [5] correlations. It has been recognized by the research of Chen *et al.*[8], Garimella [9], and Triplett *et al* [10] that surface tension force plays an important role for tubes of diameters less than 10 mm.

The two-phase flow phenomenon has been a topic of interest for the last few decades, since there is the influence of many parameters such as interaction of gravity, buoyancy, and inertia forces on the individual phases. It is also observed that flow parameters such as interaction of forces and void fraction are highly affected as flow changes in both upward and downward direction.

In inclined channel two-phase flow, the most extensive study has been reported by Begg and Brill [11], and Mukherjee and Brill [12]. The Begg and Brill [11] method remains perhaps the best known, and their correlation is based on data gathered in 90 ft (1 ft = 30.48 cm) long pipes with internal diameters 1 and 1.5 in (1 in = 2.54 cm). These pipes were inclined at various angles between 0 to 90 degrees in both upward and downward directions.

Ghajar and Tang [13] were compared the performance of 54 void fraction correlations based on unbiased experimental data set of 3385 data points. They developed a general correlation which can be applicable for all two-phase flows regardless of flow pattern, gas-liquid combination, and pipe inclination angle. This correlation is based on the drift flux model.

Recently, Venkatesan *et al.* [14] studied two-phase flow pattern and pressure drop experimentally using air-water mixtures. The tube diameters used range from 0.6-3.4 mm. They compared experimental data with existing correlations and proposed new correlation by modification of Chisholm parameter, *C*:

$$C = 4(\mathrm{We}_\mathrm{l})^{0.3}\left(\frac{\mathrm{Re}_G}{\mathrm{Re}_\mathrm{L}}\right)^{0.5} \quad \text{for Bo} > 1 \tag{1}$$

$$C = 2(\mathrm{We}_\mathrm{l})^{0.5}\left(\frac{\mathrm{Re}_G}{\mathrm{Re}_\mathrm{L}}\right)^{0.5} \quad \text{for Bo} < 1 \tag{2}$$

Many other investigators also observed that there is influence of various parameters on the value of constant, *C*. Li and Wu [15] empirically established new correlation by considering the significant effect of Bond number and Reynolds number. Similar reasonable conclusions were made by Lee and Lee [16], and English and Kandlikar [17].

Experimentation

A schematic diagram of the experimental set-up was suitably presented in our earlier article, [18]. Centrifugal pump supplies water to test section from water tank and reciprocating compressor is used to supply air. Water and air flow rates are regulated with the help of

Table 1. Two-phase drop correlations of macrochannels considered for comparison with the present experimental data

Homogeneous model	$\left(\frac{\mathrm{d}p}{\mathrm{d}l}\right)_f = \frac{2 f_{\mathrm{TP}} G^2}{D \rho_{\mathrm{TP}}}, \quad f_{\mathrm{TP}} = \frac{16}{\mathrm{Re}_{\mathrm{TP}}},$ for $R_{\mathrm{TP}} < 2000$, if $R_{\mathrm{TP}} > 2000$ then $f_{\mathrm{TP}} = 0.079\ \mathrm{Re}^{-0.25}$, $\mathrm{Re} = GD/\mu_{\mathrm{TP}}$. Three possible forms of the two-phase viscosity models are: Ma Adams *et al.* $\mu_{\mathrm{TP}} = [x/\mu_v + (1-x)/\mu_{\mathrm{L}}]^{-1}$, Cicchitti *et al.* $\mu_{\mathrm{TP}} = [x\mu_v + (1-x)\mu_{\mathrm{L}}]^{-1}$, Dukler *et al.* $\mu_{\mathrm{TP}} = \rho_{\mathrm{TP}}\, [x(\mu_v/\rho_v) + (1-x)\mu_{\mathrm{L}}/\rho_{\mathrm{L}}]$
Lockhart and Martinelli [3]	$\left(\frac{\mathrm{d}p}{\mathrm{d}z}\right)_{\mathrm{f}} = \left(\frac{\mathrm{d}p}{\mathrm{d}z}\right)_{\mathrm{L}} \varphi_{\mathrm{L}}^2, \quad \varphi_{\mathrm{L}}^2 = 1 + \frac{c}{x} + \frac{1}{x^2}, \quad X = \left[\frac{\left(\frac{\mathrm{d}p}{\mathrm{d}z}\right)_{\mathrm{L}}}{\left(\frac{\mathrm{d}p}{\mathrm{d}z}\right)_v}\right]^{0.5},$ $\left(\frac{\mathrm{d}p}{\mathrm{d}z}\right)_{\mathrm{L}} = f_{\mathrm{L}} \frac{2G^2}{D_{PL}}(1-x)^2, \quad \left(\frac{\mathrm{d}p}{\mathrm{d}z}\right)_{\mathrm{V}} = f_{\mathrm{V}} \frac{2G^2}{D_{\rho v}} x^2, \quad f_{\mathrm{L}} = \frac{16}{\mathrm{Re}_{\mathrm{l}}}$ for $\mathrm{Re}_{\mathrm{L}} < 2000$, $f_{\mathrm{L}} = 0.079\ \mathrm{Re}_{\mathrm{L}}^{-0.25}$, for $\mathrm{Re}_{\mathrm{L}} > 2000$, $f_{\mathrm{v}} = 16/\mathrm{Re}_v$, for $\mathrm{Re}_v < 2000$, for $\mathrm{Re}_{\mathrm{V}} > 2000$, $f_{\mathrm{L}} = 0.079\ \mathrm{Re}_v^{-0.25}$, $\mathrm{Re}_{\mathrm{L}} = [G(1-x)D]/\mu_{\mathrm{L}}$, $\mathrm{Re}_v = G_x D/\mu_{\mathrm{V}}$
Chisholm [4]	$\left(\frac{\mathrm{d}P}{\mathrm{d}z}\right)_{\mathrm{f}} = \left(\frac{\mathrm{d}P}{\mathrm{d}z}\right)_{\mathrm{LO}} \varphi_{\mathrm{LO}}^2, \quad \varphi_{\mathrm{LO}}^2 = 1 + (Y^2 - 1)\left[Bx^{\frac{2-n}{2}}(1-x)^{\frac{2-n}{2}} + x^{2-n}\right], \quad Y^2 = \frac{\left(\frac{\mathrm{d}P}{\mathrm{d}Z}\right)_{\mathrm{VO}}}{\left(\frac{\mathrm{d}P}{\mathrm{d}Z}\right)_{\mathrm{LO}}}$ If $0 < Y < 9.5$, $B = 55/G^{0.5}$ for $G > 1900$ kg/m^2 s, $B = 2400/G$ for $500 < G < 1900$ kg/m^{2}s, $B = 4.8$ for $G < 500$ kg/m^{2}s. If $9.5 < Y < 28$, $B = 520/YG^{0.5}$ for $G < 600$ kg/m^{2}s $B = 21/Y$ for $G > 600$ kg/m^{2}s and for $Y > 28$, $B = 15000/(Y^2 G^{0.5})$ for $G < 600$ kg/m^{2}s
Friedel [5]	$\left(\frac{\mathrm{d}p}{\mathrm{d}z}\right)_{\mathrm{f}} = \left(\frac{\mathrm{d}p}{\mathrm{d}z}\right)_{\mathrm{LO}} \varphi_{\mathrm{LO}}^2, \quad \varphi_{\mathrm{LO}}^2 = E + \frac{3.24FH}{F_r^{0.045}\ \mathrm{We}^{0.035}}, \quad F_r = \frac{G^2}{\mathrm{g}D\rho_H^2}, \quad F = x^{0.78}(1-x)^{0.224},$ $H = \left(\frac{\rho_{\mathrm{L}}}{\rho_v}\right)^{0.91} \left(\frac{\rho_v}{\rho_{\mathrm{l}}}\right)^{0.19} \left(1 - \frac{\rho_v}{\rho_{\mathrm{L}}}\right)^{0.7}, \quad \mathrm{We} = \frac{G^2 D}{\sigma \rho_H},$ $\rho_H = \left(\frac{x}{\rho_v} + \frac{1-x}{\rho_{\mathrm{L}}}\right)^{-1}, \quad E = (1-x)^2 + x\frac{\rho_{\mathrm{L}} f_{vo}}{\rho_v f_{\mathrm{LO}}}$ $f_{\mathrm{LO}} = 16/\mathrm{Re}_{\mathrm{LO}}$ for $\mathrm{Re}_{\mathrm{LO}} < 2000$, for $\mathrm{Re}_{\mathrm{LO}} > 2000$ $f_{\mathrm{lo}} = 0.079\ \mathrm{Re}_{Lo}^{-0.25}$ $f_{\mathrm{VO}} = 16/\mathrm{Re}_{\mathrm{VO}}$ for $\mathrm{Re}_{\mathrm{VO}} < 2000$, $f_{\mathrm{VO}} = 0.079\ \mathrm{Re}_{vo}^{-0.25}$ for $\mathrm{Re}_{\mathrm{VO}} > 2000$, and $\mathrm{Re}_{\mathrm{LO}} = GD/\mu_{\mathrm{L}}$ $\mathrm{Re}_{\mathrm{VO}} = GD/\mu_{\mathrm{V}}$

hand shut off and by-pass valves. Air and water are mixed in the mixing chamber. In the return line, from the mixture of air-water, air is released to the atmosphere, and the water is recirculated. Measurements of two-phase pressure drop and static pressure in the test section is carried out using differential pressure transducers with range of 0-1 bar and 0-2.5 bar, respectively.

Data acquisition receives data of pressure and temperature. Measurements of flow rates of water and air are carried out using rotameters range of 0-3 and 0-100 lpm for water and air, respectively. Static pressure of air before entering the mixing chamber is measured by using the pressure gauge of 0-10 bar range. This is used for calculation of air the density and mass flux. In this study, three test sections are used, made up of transparent acrylic material.

Test sections are circular in cross-section of 4.0, 6.0, and 8.0 mm internal diameter with length 400 mm.

Table 2. Two-phase drop correlations of mini-channels considered for comparison with the present experimental data

Zhang [19]	$C = 21\left(1 - \mathrm{e}^{\frac{-0.358}{\mathrm{La}}}\right)$, where $\mathrm{La} = \dfrac{\left[\dfrac{\sigma}{\mathrm{g}(\rho_L - \rho_\mathrm{g})}\right]^{0.5}}{d}$
Li and Wu [15]	If $\mathrm{Bo} \le 1.5,\ C = 11.9\ \mathrm{Bo}^{0.45}$ and $1.5 < \mathrm{Bo} \le 11,\ C = 109.4(\mathrm{Bo\ Re}_\mathrm{l}^{0.5})^{-0.56}$

Two-phase pressure drop data reduction

The pressure drop was obtained in test section under adiabatic condition and at 0°, 30°, 60°, and 90° orientations. The total measured pressure drop consists of three components: static pressure drop (elevation head), the momentum pressure drop (acceleration), and frictional pressure drop. Table 3 presents range of experimental parameters.

Table 3. Range of experimental parameters

	Orientation	*G* water [kgm^{-2}s^{-1}]		*G* air [kgm^{-2}s^{-1}]		*G* [kgm^{-2}s^{-1}]		*x*		Δ*P* [kPa]	
	(downward)	min	max	min	max	min	max	min	max		
4.00	0	66.31	3050.56	33.61	134.13	99.93	3184.69	0.010	0.716	4.30	57.91
	30°	66.31	3050.56	32.40	129.60	98.71	3180.16	0.010	0.709	0.13	62.05
	60°	66.31	3050.56	32.24	129.06	98.56	3179.62	0.010	0.710	4.27	62.83
	90°	66.31	3050.56	32.23	128.28	98.54	3178.84	0.010	0.708	1.32	88.15
6.00	0	29.47	471.57	14.34	57.46	43.82	529.03	0.029	0.744	3.97	9.78
	30°	29.47	471.57	14.33	57.06	43.80	528.64	0.029	0.744	0.05	7.41
	60°	29.47	471.57	14.31	56.94	43.79	528.51	0.029	0.744	0.40	5.17
	90°	29.47	471.57	14.31	56.52	43.79	528.10	0.029	0.742	0.16	5.53
8.00	0	16.58	829.02	8.35	33.60	24.93	862.62	0.010	0.751	4.84	11.33
	30°	16.58	928.50	8.37	33.30	24.95	961.81	0.008	0.752	5.83	11.21
	60°	16.58	928.50	8.38	33.59	24.96	962.09	0.008	0.752	5.75	12.12
	90°	16.58	928.50	8.36	33.67	24.94	962.18	0.008	0.716	7.78	14.80

$$\left(\frac{\mathrm{d}P}{\mathrm{d}z}\right)_T = \left(\frac{\mathrm{d}P}{\mathrm{d}z}\right)_\mathrm{s} + \left(\frac{\mathrm{d}P}{\mathrm{d}z}\right)_\mathrm{m} + \left(\frac{\mathrm{d}P}{\mathrm{d}z}\right)_\mathrm{f} \tag{3}$$

For the steady-state flow conditions in the horizontal and inclined channel of circular cross-section, momentum pressure drop considered as negligible:

$$\left(\frac{\mathrm{d}P}{\mathrm{d}z}\right)_\mathrm{m} = 0 \tag{4}$$

The total pressure drop can be expresse:

$$\left(\frac{\mathrm{d}P}{\mathrm{d}z}\right)_T = \left(\frac{\mathrm{d}P}{\mathrm{d}z}\right)_\mathrm{s} + \left(\frac{\mathrm{d}P}{\mathrm{d}z}\right)_\mathrm{f} \tag{5}$$

The static pressure drop can be calculated:

$$\left(\frac{\mathrm{d}P}{\mathrm{d}z}\right)_\mathrm{s} = \rho_\mathrm{m} \mathrm{g} H \sin\theta \tag{6}$$

where ρ_m is the mixture density:

$$\rho_\mathrm{m} = \varepsilon \rho_G + (1-\varepsilon)\ \rho_\mathrm{L} \tag{7}$$

During this study, the void fraction is determined by using Ghajar and Tang [13] correlation, which in turns used for calculation of static pressure drop:

$$\varepsilon = \frac{V_\mathrm{sg}}{C_o (V_\mathrm{sg} + V_\mathrm{sl}) + u_{gm}} \tag{8}$$

$$C_o = \frac{v_\mathrm{sg}}{v_\mathrm{sg} + v_\mathrm{sl}} \left[1 + \left(\frac{v_\mathrm{sl}}{v_\mathrm{sg}} \right)^{(\rho_\mathrm{g}/\rho_\mathrm{l})^{0.1}} \right] \tag{9}$$

$$u_\mathrm{gm} = 2.9\left(1.22 + 1.22\sin\theta\right)^{\frac{P_\mathrm{atm}}{P_\mathrm{sys}}} \left[\frac{\mathrm{g} D \sigma (1+\cos\theta)(\rho_\mathrm{l} - \rho_\mathrm{g})}{\rho_\mathrm{e}^2} \right] \tag{10}$$

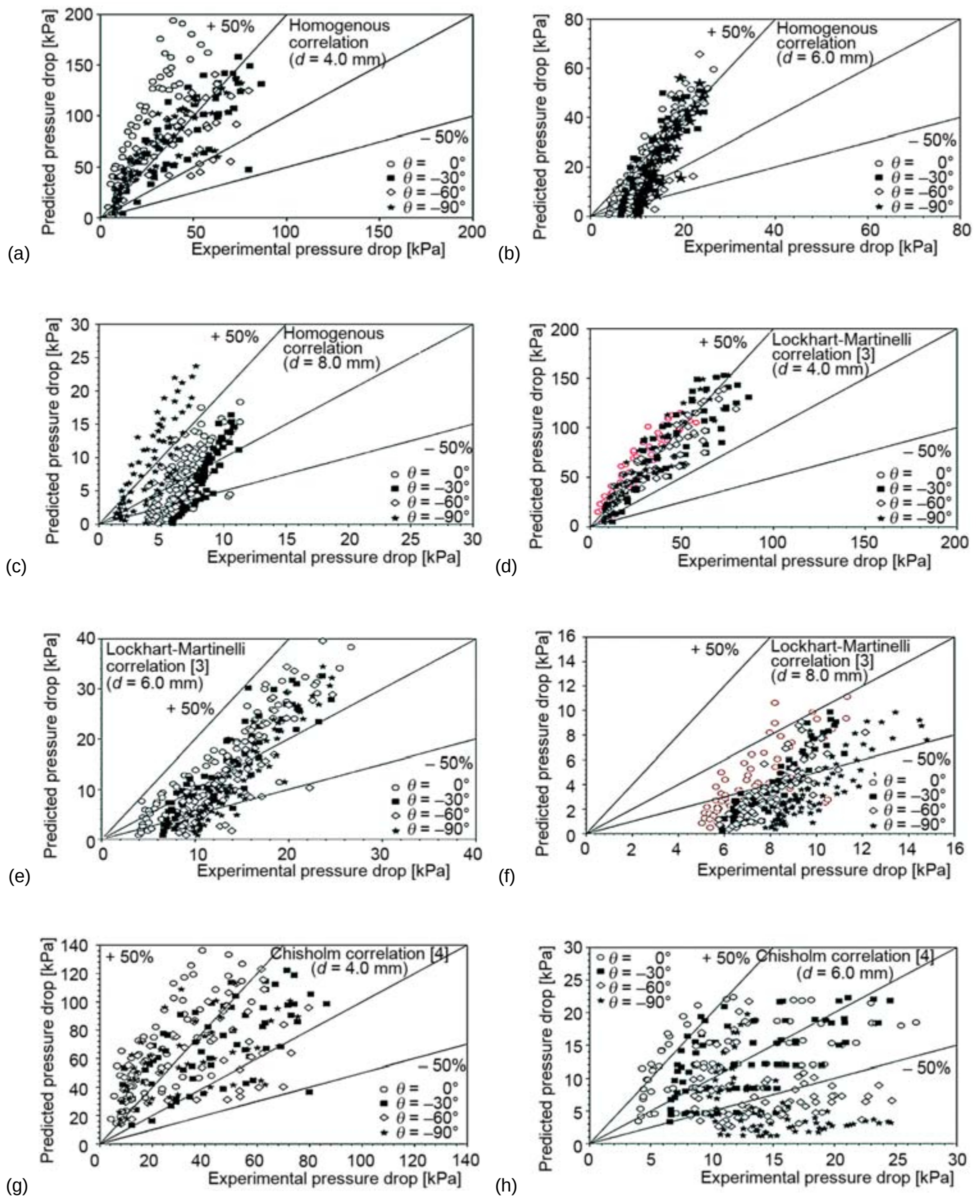
$$\Delta P_\mathrm{TP} - \Delta P_\mathrm{static} = \Delta P_\mathrm{friction} \tag{11}$$

Comparison with existing correlation

The experimentally measured two-phase pressure drop data has been compared with the existing correlations (tab. 1). The correlations considered for comparisons are homogeneous [3-5]. These correlations are well accepted and generally used for calculation of two-phase pressure drop of macro scale channels. Li and Wu [15] and Zhang [19] correlations are particularly developed from the data associated to mini and micro-channels. These are also considered for comparison with present experimental data.

Figure 1(a) shows that comparisons of 4.0 mm tubes measured data with homogenous correlation. It is observed that the results of predictions over predicts data of horizontal orientation and of other two specified inclination settings. The comparisons of 6.0 mm tube data with homogeneous correlation at 0° to –90° inclinations are representing good trend, but most of the data fall fairly superficial to the acceptable reign as shown in fig. 1(b). Figure 1(c) presents the comparison of measured data of 8.0 mm tube at different orientations with homogenous correlation, predicted results are within the ±50% error band. The Lockhart-Martinelli correlation [3] does not work very well for predictions of 4.0 and 8.0 mm tube measured data points. However, it is observed that nearly 77% data of the 6.0 mm tube at all orientations are lies in the acceptable range as shown in figs. 1(d)-(f). Figures 1(g)-(i) show the comparison between the experimental data and predicted values of Chisholm correlation

[4]. It can be observed from figs. 1(g) and (i) that the Chisholm correlation over predicts data of 4.0 mm tube and underestimates 8.0 mm tube data. Figure 1(h) presents most of data of 6.0 mm tube are within the specified ±50% error band limit, but it does not represent any trend. Friedel correlation [5] very much underestimates experimental data for all 4.0, 6.0, and 8.0 mm tubes at specified orientations, it can be seen in figs. 1(j)-(l), respectively. It can be seen from the comparison presented in figs. 2(m-o) that the Zhang correlation [19] under predicts most of the experimental results of 6.0 and 8.0 mm tubes. However, the disparity is adequately less for the smaller 4.0 mm tube data at all four mentioned orientations.



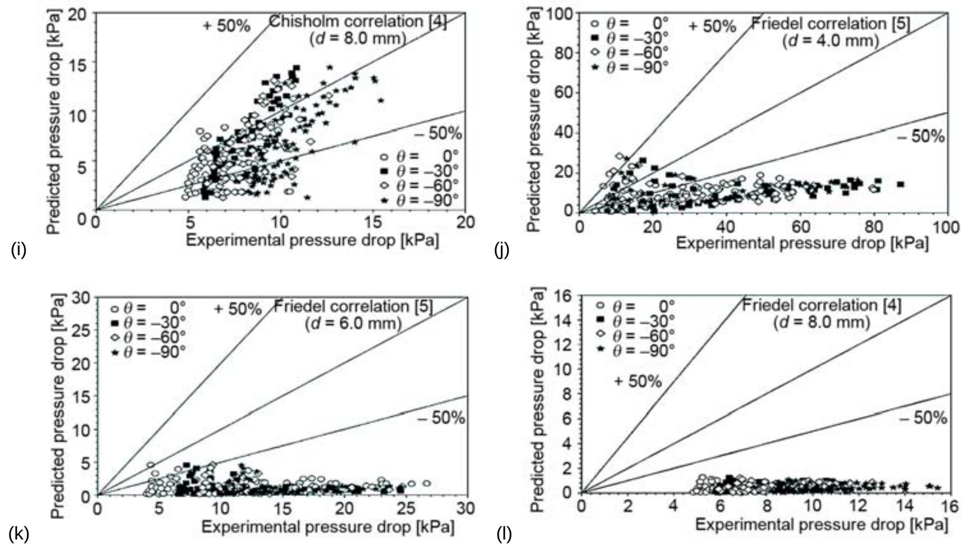


Figure 1. Comparison of the experimental two-phase pressure drop with existing macro channel correlations

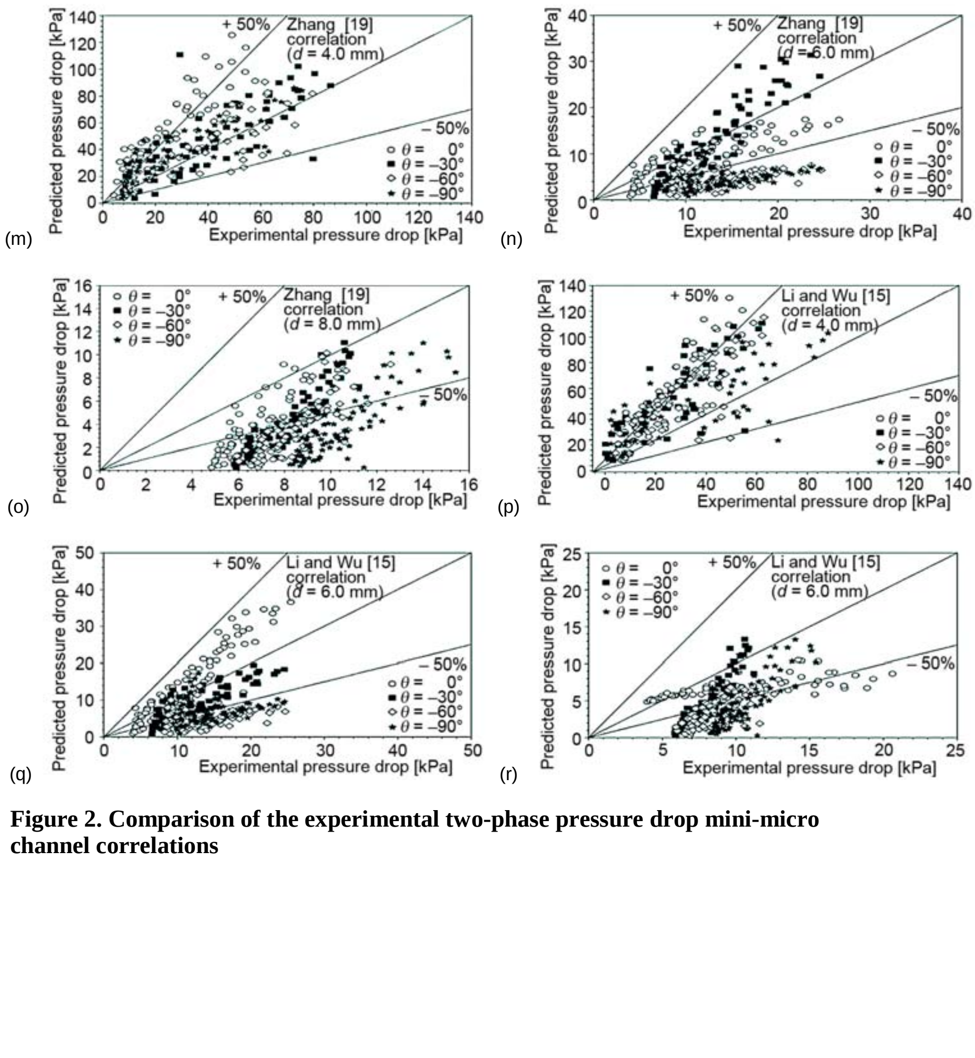


Figure 2. Comparison of the experimental two-phase pressure drop mini-micro channel correlations

Table 4. Mean deviation e_R, standard deviation e_N, and percentage of data points λ within ±50% error band for the considered correlations with air-water mixture data

Diameter [mm]	Data points λ	Angle (downward)	Correlation											
			Homogenous			Lockhart-Martinelli [3]			Chisholm [4]			Friedel [5]		
			e_R	σ_N	λ	e_R	σ_N	λ	e_R	σ_N	λ	e_R	σ_N	λ
4.00	56	0	277.85	128.74	02	180.5	140.60	11	210.29	146.60	04	63.19	21.62	08
	69	30°	21128.6	12251.9	0	55.06	52.30	41	102.022	100.511	26	74.74	20.80	11
	58	60°	117.38	95.13	13	65.42	68.03	33	125.58	103.113	17	74.26	25.95	08
	57	90°	125.20	77.09	08	181.77	328.58	01	125.98	105.38	19	70.63	20.04	11
6.00	85	0	82.47	46.09	23	33.86	19.23	71	49.18	44.02	57	85.76	145.92	03
	79	30°	68.78	45.14	27	30.30	22.99	63	34.77	27.46	56	90.23	11.73	02
	79	60°	66.15	43.67	34	35.91	23.93	56	54.81	20.24	26	91.63	9.688	0
	75	90°	59.36	37.90	32	37.97	24.35	55	64.52	27.91	21	92.97	24.30	0
8.00	70	0	43.82	26.52	45	52.07	25.37	35	37.45	55.00	48	92.81	4.54	0
	81	30°	41.48	26.99	50	57.78	23.89	26	33.15	21.89	56	93.56	3.58	0
	80	60°	45.84	25.73	41	31.81	260.00	22	35.70	23.20	54	98.95	10.96	0
	84	90°	115.28	80.0	21	66.79	19.17	17	39.09	24.45	51	96.45	2.40	0

Table 5. Mean deviation e_R, standard deviation e_N, and percentage of data points λ within ±50% error band for the considered correlations with air-water mixture data

Diameter [mm]	Data points λ	Angle (Downward)	Correlation					
			Zang [19]			Li and Wu [15]		
			e_R	σ_N	λ	e_R	σ_N	λ
4.00	56	0	109.49	78.10	15	116.35	80.33	14
	69	30°	42.85	48.33	52	419.57	1620.44	11
	58	60°	52.55	56.09	40	94.06	69.55	16
	57	90°	47.48	50.19	42	159.80	289.41	29
6.00	85	0	34.90	20.67	65	37.73	20.47	62
	79	30°	29.78	22.77	64	33.78	22.13	60
	79	60°	64.23	20.21	12	61.89	21.05	15
	75	90°	68.63	18.02	09	54.48	19.91	22
8.00	70	0	53.42	25.29	28	30.32	18.47	57
	81	30°	54.81	24.69	32	48.87	25.65	41
	80	60°	58.65	20.08	23	62.82	17.98	62
	84	90°	65.04	20.46	18	58.69	24.10	24

$$e_R = \frac{1}{N_p} \sum_{i=1}^{N_p} \frac{\left(\frac{\mathrm{d}p}{\mathrm{d}z}_{\text{Predicted}} - \frac{\mathrm{d}p}{\mathrm{d}z}_{\text{expt}} \right)}{\frac{\mathrm{d}p}{\mathrm{d}z}_{\text{expt}}} \cdot 100, \qquad \sigma_N = \sqrt{\frac{\sum_{I=1}^{N_p} (e_i - e_R)^2}{N_p - 1}} \tag{12}$$

λ is predicted data points within ±50% deviation.

Figures 2(p)-(r) show the comparison of experimental pressure drop in the 4.0, 6.0, and 8.0 mm tubes with Li and Wu model [15]. It may be inferred that Li and Wu correlation cannot be able to predict present frictional pressure drop data up to satisfactory level for all tubes at different orientations.

A summary of the comparison of experimental data with considered correlations is given in tabs. 4 and 5, which includes mean deviation, standard deviation, and percentage of data points within ±50% error band.

Development of new correlation

In the present study, the predictive capabilities of correlations considered for calculation of two-phase frictional pressure drop were assessed. It can be observed that these correlations are not adequate to predict the experimental pressure drop data at the satisfactory level. Hence, it is decided to develop new correlation by making some modifications in existing correlation of two-phase flow.

Lockhart-Martinelli [3] presented correlation for prediction of frictional pressure drop based on a two-phase multiplier as given in tab. 1. Later, Chisholm [4] developed the following correlations for calculation of the correction factor in two-phase flow resistance. Where, constant C is selected entirely depends upon nature of the flow regime of the liquid and gas phases. It lies in the range of 5-20: C = 5 (laminar flow of liquid-laminar flow of gas), C = 10 (turbulent flow of liquid-laminar flow of gas), C = 12 (laminar flow of liquid-turbulent flow of gas), and C = 20 (turbulent flow of liquid – turbulent flow of gas). It is clearly understood from eqs. (13) and (14) that the multiplier φ_{L}^2 is not only depended upon the Martinelli parameter, χ but also of the flow recognizing characteristics of the liquid and gas phases.

$$\varphi_{\mathrm{L}}^2 = 1 + \frac{C}{\chi} + \frac{1}{\chi^2} \tag{13}$$

$$\varphi_G^2 = 1 + C\chi + \chi^2 \tag{14}$$

Figure 3 shows comparison of the calculated correction factor φ_{L}^2 and the experimental correction factor *vs.* Martinelli parameter. The lines presented in the figures are of theoretical values of the correction factor considered for four values of constant C in the range of C = 5-20. During present experimentation, two flow types of flow regimes are observed; laminar flow of water-turbulent flow of air and turbulent flow water-turbulent flow of air, *e. g. L-T*, *T-T*. The experimental values of correction factors are not fall in the expected range for all diameter tubes and at specified orientation. It can be observed that the experimental values of constant C are to be significantly affected by varies two-phase parameters.

Theoretically, there are four forces related to two-phase flow in channels: gravitational, inertia, viscous, and surface-tension forces. The relative significances of all these forces are considered for calculation of two-phase frictional pressure drop, which is in turn, depends upon size and orientation of test section. The effects of these forces can be incorporated in terms of dimensionless numbers. Moreover, these forces are included in this study for pressure drop estimation in the form of Reynolds, Froude, and Bond numbers.

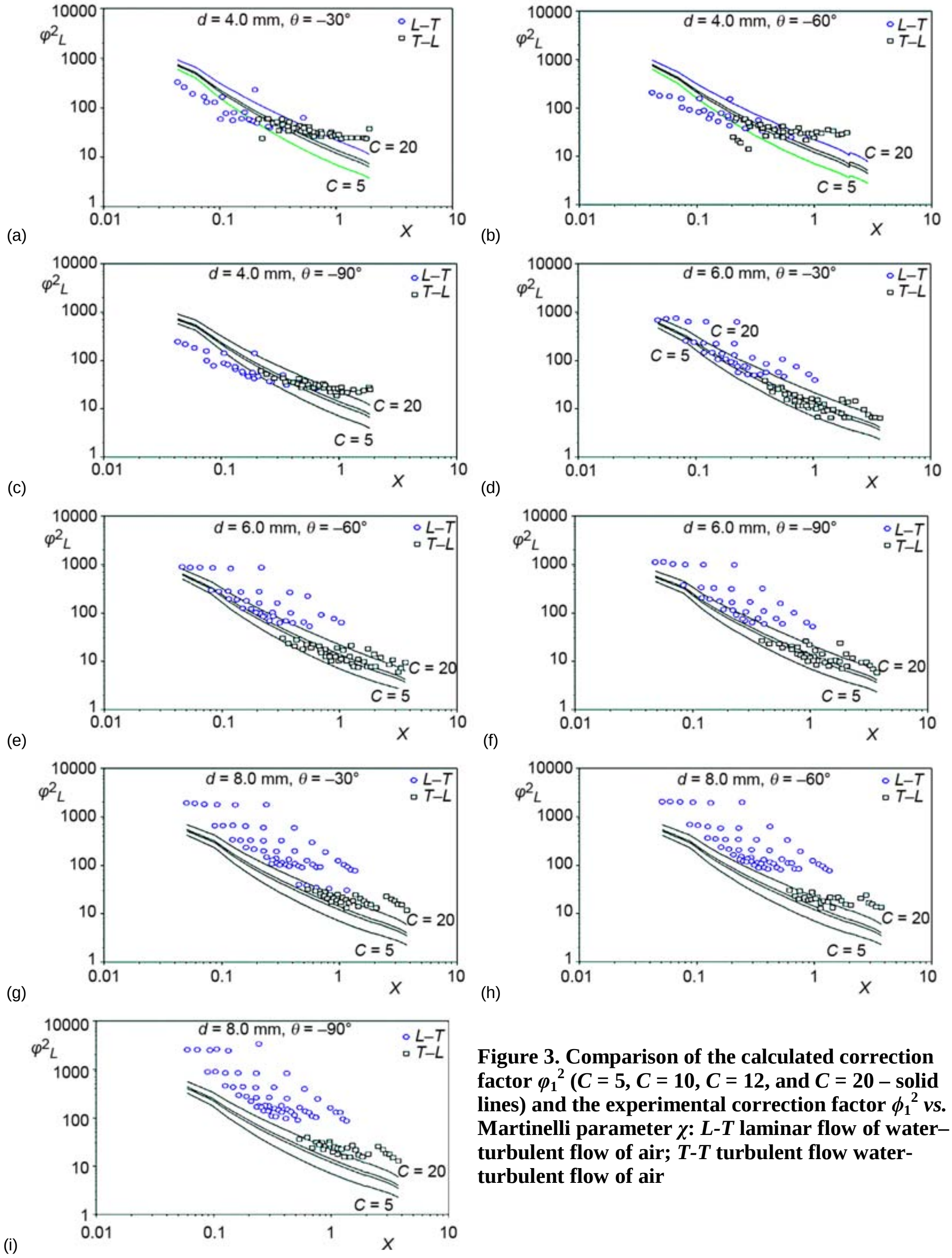


Figure 3. Comparison of the calculated correction factor φ_1^2 (C = 5, C = 10, C = 12, and C = 20 – solid lines) and the experimental correction factor ϕ_1^2 *vs.* Martinelli parameter χ: *L-T* laminar flow of water–turbulent flow of air; *T-T* turbulent flow water-turbulent flow of air

The Bond number measures the importance to 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 the channel hydraulic diameter becomes smaller, the bubbles are squeezed in the flow channel and surface tension gradually dominates the flow. The Reynolds number gives a measure as the ratio of inertia forces to viscous forces and consequently, quantifies the relative importance of these two types of forces for given flow conditions. Reynolds number plays an important role in characterizing different flow regimes, such as laminar and turbulent flow. Laminar flow occurs at low Reynolds numbers where viscous forces are predominant while turbulent flow occurs at high Reynolds numbers and is dominated by inertia forces [15]. As the mass flux of liquid and air increases due to this there is larger interaction between the fluids, inertia forces dominate. An increase in the pressure drop occurred with the increase in mass flux and decrease in tube diameter. It is evident that the effect of gravitational force taken into account for calculation of pressure drop in inclined tubes. Froude number is dimensionless parameter measuring of the ratio of the inertia force on element of fluid to the weight of the fluid element. The high Froude number shows that the inertia forces are significantly larger than the gravitational effect.

Diameters of test section used in this study is exceeding range of mini channel and starting of macro channel. The precise definition of micro channel is subject to disagreement. The channel classification was developed by Kandlikar and Grande; it can be used for consideration of minichannels to be within range of 3 mm $\geq$ D $\geq$ 200 μm [17]. However, minichannels, macrochannels and conventional channels are characterized as channels with the hydraulic diameter between 0.2-3.0 mm, 3.0-6.0 mm and above 6.0 mm, respectively.

After considering the significant effects of abovementioned parameters, subsequently based on the analysis of present experimental frictional pressure drop data a correlation has been proposed for predicting Chisholm parameter constant C of small-diameter tubes. In this correlation, the parameter C is a function of Martinelli parameter χ, and Reynolds, Froude, and Bond numbers. The proposed correlation is derived using multiple regression analysis. Total 862 data points considered for development of new correlation. The effects of many other non-dimensional numbers also investigated in this study, which are not covered in this paper.

$$C = 0.0082(\mathrm{Re_L})^{2.0508}(\mathrm{Fr})^{-1.2857}(\mathrm{Bo})^{5.436} \quad \text{for Bo} < 0.5 \tag{15}$$

$$C = 397.22(\mathrm{Re_L})^{-0.0256}(\mathrm{Fr})^{-0.0256}(\mathrm{Bo})^{0.3993} \quad \text{for Bo} > 0.5 \tag{16}$$

Figure 4 presents the comparison between predicted pressure drop and experimental data using eqs. (15) and (16). As can be noted, proposed correlation predicts frictional pressure drop data for all diameter tubes at various specified orientations, which are within ±50% error band. Table 6 presents data of comparison with proposed correlation, which includes mean deviation, standard deviation, and percentage of data points within ±50% error band.

Conclusions

Based on 862 data points collected from experimental results and six existing correlations to predict two-phase pressure drop were evaluated. A new correlation is proposed to compute the frictional pressure drop in small diameter inclined tubes. Following conclusions were drawn.

- After evaluation of experimental two-phase frictional pressure drop using existing correlations none of it shows satisfactory agreement for all diameter tubes.

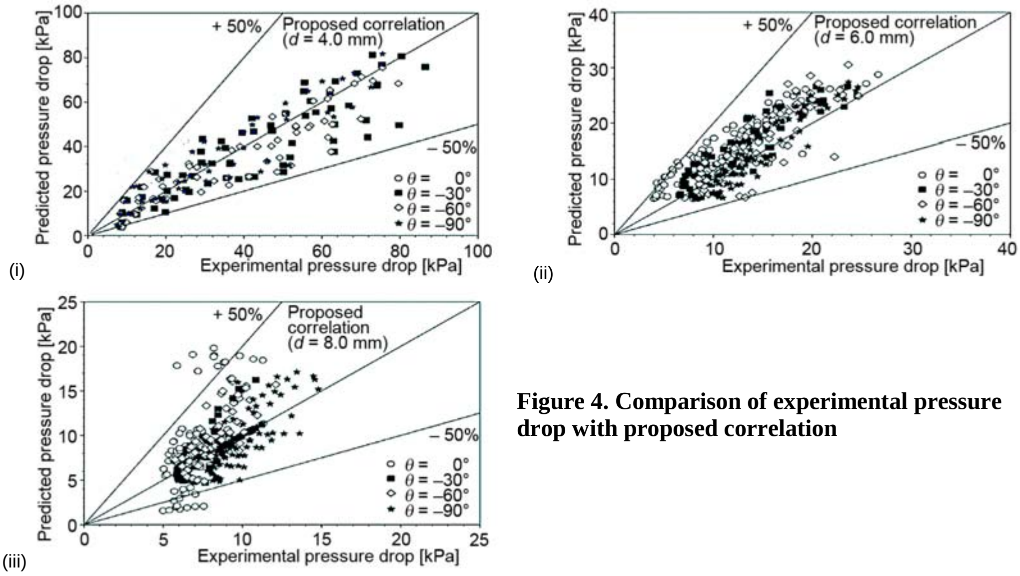


Figure 4. Comparison of experimental pressure drop with proposed correlation

Table 6. Mean deviation e_R, standard deviation e_N, and percentage of data points λ within ±50% error band for the proposed correlation with air-water mixture data

Diameter [mm]	Data points λ	Angle (Downward)	Developed correlation		
			e_R	σ_N	λ
4.00	50	0	51.50	29.52	27
	68	30°	22.55	16.95	63
	54	60°	22.04	16.82	50
	55	90°	21.15	29.95	49
6.00	85	0	44.14	29.20	55
	78	30°	24.29	16.49	71
	79	60°	19.94	13.34	78
	73	90°	16.22	11.54	72
8.00	79	0	35.62	27.28	59
	78	30°	24.71	18.99	68
	80	60°	66.10	77.30	49
	83	90°	19.17	13.44	81

- The constant C, in the Chisholm parameter is not only depends upon the Martinelli parameter, χ but also affected by many factors. As proposed in new correlation it is depends upon the Reynolds number of liquid, Froude and Bond numbers.

Nomenclature

Bo – Bond number [$= g(\rho_l - \rho_g)D^2/\sigma$]
C – constant in Chisholm correlation
C_0 – two-phase distribution coefficient
D – tube diameter
E – variable in Friedel correlation
Fr – Froude number, ($= G^2/gD\rho^2_m$)

F – variable in Friedel correlation
F – friction factor
G – mass flux, [kgm^{-2}s^{-1}]
g – gravitational acceleration, [ms^{-2}]
H – variable in Friedel correlation
N – total number of data points
P_{atm} – atmosphere pressure, [Nm^{-2}]
P_{sys} – system pressure, [Nm^{-2}]
ΔP – pressure drop, [kPa]
Re – Reynolds number
u_{gm} – gas drift velocity, [ms^{-1}]
V_{sg} – superficial gas velocity, [ms^{-1}]
V_{sl} – superficial liquid velocity, [ms^{-1}]
We – Weber number, (= $G^2D/\sigma\rho_m$)
x – mass fraction

Greek symbols

$\varphi^2{}_i$ – two-phase multiplier for liquid flowing alone
χ – Martinelli parameter
μ – dynamic viscosity, [Nsm^{-2}]
ρ – density, [kgm^{-3}]
ρ_m – mixture density, [kgm^{-3}]
σ – surface tension of liquid, [Nm^{-1}]
ε – void fraction
θ – inclination angle, [rad]

Subscripts

G – gas phase only
L – liquid phase only
TP – two-phase

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