EXPERIMENTAL STUDY ON TWO-PHASE PRESSURE DROP OF AIR-WATER IN SMALL DIAMETER TUBES AT HORIZONTAL ORIENTATION

by

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Experimental results of adiabatic two-phase pressure drop in small diameter tubes are presented in this work. Air-water mixture is used as the working substance. Four test sections made of transparent acrylic tubes of different internal diameters ranging from 3.0 mm to 8.0 mm are used with different test section lengths from 150 mm to 400 mm. The investigation is carried out within the range of mass flux of water 16.58-3050 kg/m²s, mass flux of air 8.25-204.10 kg/m²s, and total mass flux of 99.93-3184.69 kg/m²s. Some of the existing correlations for macro- and mini-channels are compared with the experimental data. Based on the experimental data a new correlation has been developed to predict two-phase pressure drop in horizontal channels.

Key words: *two-phase flow, air-mater, pressure drop, small diameter, horizontal tubes*

Introduction

Most of the research reported on two-phase flow behavior deals with the circular tube larger than 10 mm in diameter. However, recently research direction is focused on two-phase flow in small diameter tubes (including narrow rectangular channels with their hydraulic diameters less than 5 mm) [1, 5, 8, 9, 10, 12]. Prediction of local heat transfer coefficients and total pressure gradients are required for design of industrial equipments in order to reduce the costs, optimize performance and save energy [11]. The pressure drop in two-phase flow is an important parameter in many engineering applications such as chemical, nuclear, petroleum, refrigeration and air-conditioning industries. Total pressure drop of two-phase flow in pipes consists of the frictional, acceleration and gravitational components. In the present work, the objective is to generate experimental data of two-phase pressure drop and develop a generalized correlation to predict pressure drop. This paper is focused upon the comparison of experimental pressure drop data of air-water, adia-

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batic two-phase flow in small diameter tubes at horizontal position with available correlations and developing generalized correlation to predict two-phase pressure drop.

Experimental investigation

An experimental facility was designed and fabricated for this study to allow a detailed and accurate investigation of two-phase pressure drops of air water mixture in small diameter tubes.

Experimental set-up

A schematic diagram of the experimental set-up is shown in fig. 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° to + 90°and –90°.

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. The 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 re-circulated.

In this experiment, four different diameters test sections are used. These are made up of transparent acrylic material with circular cross-section, with a total length 600 mm and internal diameters of 3.0, 4.0, 6.0, and 8.0 mm.The total length of test section is divided into 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, and (3) outlet segment 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 are measured: flow rates of air and water, pressure drop and temperature recorded by a data acquisition system in the test section. Two rotameters are used in this experiment to measure the mass flow rates. One was used for water flow line having a range of 0.3-3.0 LPM while the other was used in the air line having a range of 10.0-100 LPM. A pressure gauge is located just before the inlet to the mixing chamber (range of 0-150 lb/in^2).This is used to measure the static pressure of air for calculation of density.

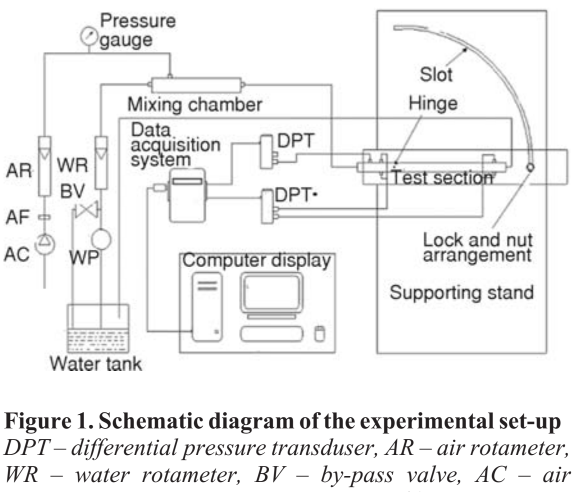

Figure 1. Schematic diagram of the experimental set-up
DPT – differential pressure transduser, AR – air rotameter, WR – water rotameter, BV – by-pass valve, AC – air compressor, WP – water pump, AF – air filter

Mixing chamber

The design of the mixing chamber is complex. 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 fig. 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 strip 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.

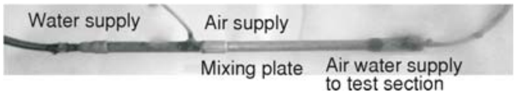

Figure 2. Mixing chamber

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.

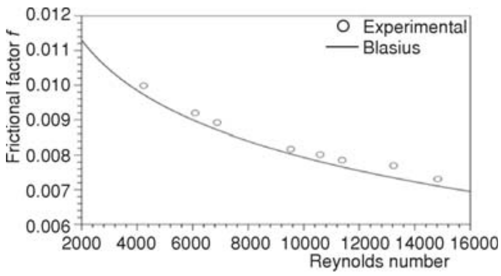

Figure 3. Comparison of experimental single-phase friction factor with Blasius correlation

Two-phase flow frictional pressure drop

The investigation was carried out using adiabatic air-water flow in small diameter tubes at horizontal position. The range of various parameters observed in experimentation using different diameter test sections is presented in tab. 1. Total number of data points collected during this study are 254.

Table 1. Experimental observation

d [mm]	N	G_{air} [kgm^{-2}s^{-1}]		G_{water} [kgm^{-2}s^{-1}]		G_{total} [kgm^{-2}s^{-1}]		x		Δp [kPa]		Re_L		Re_g	
		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
3.00	19	61.04	121.80	117.90	1179.0	178.94	1300.82	0.049	0.756	0.31	53.04	353.00	3530	9674	19303
4.00	73	33.55	204.10	66.31	3050.55	99.93	3184.69	0.010	0.750	4.30	64.26	264.73	12177	7089	43127
6.00	85	14.31	86.23	29.47	1650.51	309.05	675.70	0.008	0.744	3.97	26.65	176.48	9983	4538	27332
8.00	81	8.25	50.53	16.58	829.02	273.54	647.42	0.010	0.751	0.005	11.33	132.37	6618	3490	21354

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

Homogeneous model [1]	$\left(\frac{dp}{dl}\right)_f = \frac{2 f_{TP} G^2}{D\rho_{tp}}$ $f_{TP} = \frac{16}{Re_{TP}}$ for $R_{TP} < 2000$: if $R_{TP} > 2000$, then $f_{TP} = 0.079 Re^{-0.25}$, $Re = \frac{GD}{\mu_{TP}}$ The two-phase viscosity model of: Mc Adams *et. al* [1] $\mu_{TP} = \left(\frac{x}{\mu_v} + \frac{1-x}{\mu_L}\right)^{-1}$
Lockhart and Martinelli [2]	$\left(\frac{dp}{dz}\right)_f = \left(\frac{dp}{dz}\right)_L \phi_L^2$, $\phi_L^2 = 1 + \frac{c}{x} + \frac{1}{x^2}$, $X = [(dp/dz)_L / (dp/dz)_v]^{0.5}$, $\left(\frac{dp}{dz}\right)_L = f_L \frac{2G^2}{D_{PL}}(1-x)^2$, $\left(\frac{dp}{dz}\right)_V = f_V \frac{2G^2}{D_{\rho v}} x^2$ $f_L = \frac{16}{Re_l}$ for $Re_L < 2000$, $f_L = 0.079 Re_L^{-0.25}$ for $Re_L > 2000$, $f_V = \frac{16}{Re_V}$ for $Re_V < 2000$, for $Re_V > 2000$ $f_L = 0.079 Re_V^{-0.25}$, $Re_L = \frac{G(1-x)D}{\mu_L}$, $Re_V = \frac{G_x D}{\mu_V}$
Chisholm [3]	$\left(\frac{dP}{dz}\right)_f = \left(\frac{dP}{dz}\right)_{LO} \phi_{LO}^2$, $\phi_{LO}^2 = 1 + (Y^2 - 1)\left[Bx^{\frac{2-n}{2}}(1-x)^{\frac{2-n}{2}} + x^{2-n}\right]$ $Y^2 = (dP/dZ)_{VO} / (dP/dZ)_{LO}$. If $0 < Y < 9.5$, $B = \frac{55}{G^{0.5}}$ for $G > 1900$ kg/m²s, $B = \frac{2400}{G}$ for $500 < G < 1900$ kg/m²s, $B = 4.8$ for $G < 500$ kg/m²s. If $9.5 < Y < 28$, $B = \frac{520}{YG^{0.5}}$ for $G < 600$ kg/m²s, $B = \frac{21}{Y}$ for $G > 600$kg/m²s and for $Y > 28$, $B = \frac{1500}{Y^2 G^{0.5}}$ for $G < 600$ kg/m²s
Friedel [4]	$\left(\frac{dp}{dz}\right)_f = \left(\frac{dp}{dz}\right)_{LO} \phi_{LO}^2$, $\phi_{LO}^2 = E + \frac{3.24 FH}{F_r^{0.045} W_e^{0.035}}$, $F_r = \frac{G^2}{gD\rho_H^2}$ $F = x^{0.78}(1-x)^{0.224}$, $H = \left(\frac{\rho_L}{\rho_v}\right)^{0.91}\left(\frac{\rho_v}{\rho_l}\right)^{0.19}\left(1 - \frac{\rho_v}{\rho L}\right)^{0.7}$, $We = \frac{G^2 D}{\sigma\rho_H}$, $\rho_H = \left(\frac{x}{\rho_v} + \frac{1-x}{\rho_L}\right)^{-1}$, $E = (1-x)^2 + x\frac{\rho_L f_{vo}}{\rho_v f_{LO}}$, $f_{LO} = \frac{16}{Re_{LO}}$ for $Re_{LO} < 2000$ For $Re_{LO} > 2000$ $f_{LO} = 0.079\, Re_{LO}^{-0.25}$ $f_{VO} = \frac{16}{Re_{VO}}$ for $Re_{VO} < 2000$, $f_{VO} = 0.079\, Re_{VO}^{-0.25}$ for $Re_{VO} > 2000$ and $Re_{LO} = \frac{GD}{\mu_L} Re_{VO} = \frac{GD}{\mu_V}$

Comparison of the experimental data with the existing correlations

The experimental two-phase pressure drop data is compared with the some of the existing correlation of the macro-channel and mini-channels. Tables 2 and 3 shows the correlations considered for comparison.

Table 3. Two-phase pressure drop correlations of mini-channels considered for comparison with the present experimental data

Mishima and Hibiki [5]	Modified Lockhart -Martinelli model, where the constant C in equation $C = 21\,(1 - e^{-3019D})$
Zhang and Mishima [6]	$C = 21\left(1 - e^{\frac{-0.358}{la}}\right)$ where $la = \dfrac{\left(\dfrac{\sigma}{g(\rho_L - \rho_g)}\right)^{0.5}}{d}$
Li and Wu [7]	If Bo ≤ 1.5, C = 11.9 $Bo^{0.45}$ and 1.5 < Bo ≤ 11, $C = 109.4\,(Bo\,Re_l^{0.5})^{-0.56}$

Figure 4(a) shows the comparison of experimental frictional pressure drop data with the predictions of the homogeneous flow model. Two-phase flow homogenous viscosity is cal-

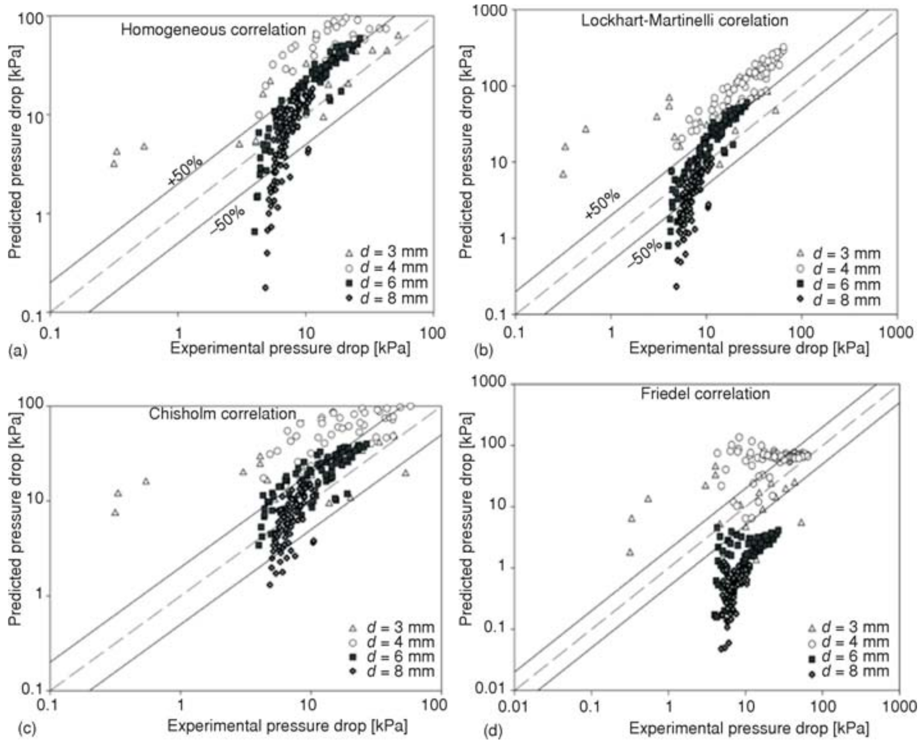

Figure 4. Comparison of the experimental pressure drop data with macro-channel correlations (a) homogeneous correlation, (b) Lockhart-Martinelli correlation, (c) Chisholm correlation, (d) Friedel correlation

culated using McAdam *et al*. [1] correlation. This correlation over predicts for 4.0 mm diameter tube frictional pressure drop data. Only 2.73% data points are within the ±50% error band. The frictional pressure drop data points of 3.0 mm, 6.0 mm, and 8.0 mm diameter tubes are 42.00%, 27.00%, and 55.00% within the ±50% error band, respectively.

Figure 4(b) shows the comparison of experimental frictional pressure drop data with the Lockhart-Martinelli [2]. The prediction is not satisfactory for all diameter tubes data used in this study. Total numbers of data point within the ±50 % error band are 30%.

Table 4 gives the statistics of the evaluated correlation for two-phase flow frictional pressure drop data for various diameter tubes used in this study.

Table 4. Statistics of the evaluated correlation for friction pressure drop data

Diameter [mm]	3.00		4.00		6.00		8.00	
Correlations	e_R	σ_N	e_R	σ_N	e_R	σ_N	e_R	σ_N
Homogeneous [1]	224.77	335.90	277.34	122.44	82.47	46.36	43.82	26.35
Lockhart--Martinelli [2]	915.81	1457.09	299.06	123.76	75.31	46.57	46.86	27.51
Chisholm [3]	108.45	361.23	237.69	159.22	75.25	49.86	34.43	21.52
Friedel [4]	394.47	655.43	62.31	23.16	81.04	14.21	92.13	4.25
Mishima-Hibiki [5]	955.60	1510.52	240.81	107.65	68.20	36.19	40.54	24.92
Zhang-Mishima [6]	701.46	1160.46	124.72	77.35	31.88	20.46	40.14	27.08
Li and Wu [7]	658.22	1084.25	130.92	78.72	38.92	20.41	46.86	27.51

Mean or average deviation
$$e_R = \sum_{i=1}^{Np} \frac{\left(\frac{dp}{dz_{\text{Predicter}}} - \frac{dp}{dz_{\text{Expt}}}\right)}{\frac{dp}{dz}} 100$$

Standard deviation
$$\sigma_N = \sqrt{\frac{\sum_{I=1}^{Np}(e_i - e_R)^2}{N_p - 1}}$$

The comparison with the Chisholm [3] and Friedel [4] correlations are presented in fig. 4 (c and d) these correlations are not able to predict frictional pressure drop data with satisfactory agreement. On other hand these correlations over predicts the 4.0 mm diameter tube data. Chisholm correlation predicts 37% of data points of 6.0 mm diameter tube within the ±50% error band while Friedel correlation underestimate the 6.0 mm and 8.0 mm diameter tubes experimental values.

Figure 5(e, f, and g) shows the comparison of experimental pressure drop with mini-channel correlation predicted values. Mishima-Hibiki [5], Zhang-Mishima [6] and Li and Wu [7] co-correlation are considered for comparison. Out of these Zhang-Mishima [6] and Li and Wu [7] model are able to catch experimental trend of 6.0 mm diameter tube while Mishima-Hibiki [5] model partially over predicts. All these models show the comparatively same over predicted data point's trend for 3.0 mm and 4.0 mm diameter tubes. Predicted pressure drop data points using Mishima-Hibiki [5], Zhang-Mishima [6] and Li and Wu [7] correlations for 6.0 mm are 32%, 85% and 52% inside the ±50% error band region, respectively, and 8.0 mm diameter tubes are 61%, 54%, and 52% fall within ±50% error band, respectively.

Therefore it could be concluded that the existing correlations developed for mini and micro channels work relatively better for evaluation of frictional pressure drop small diameter tubes (D < 8.00 mm) than that of correlations developed for macro channels.

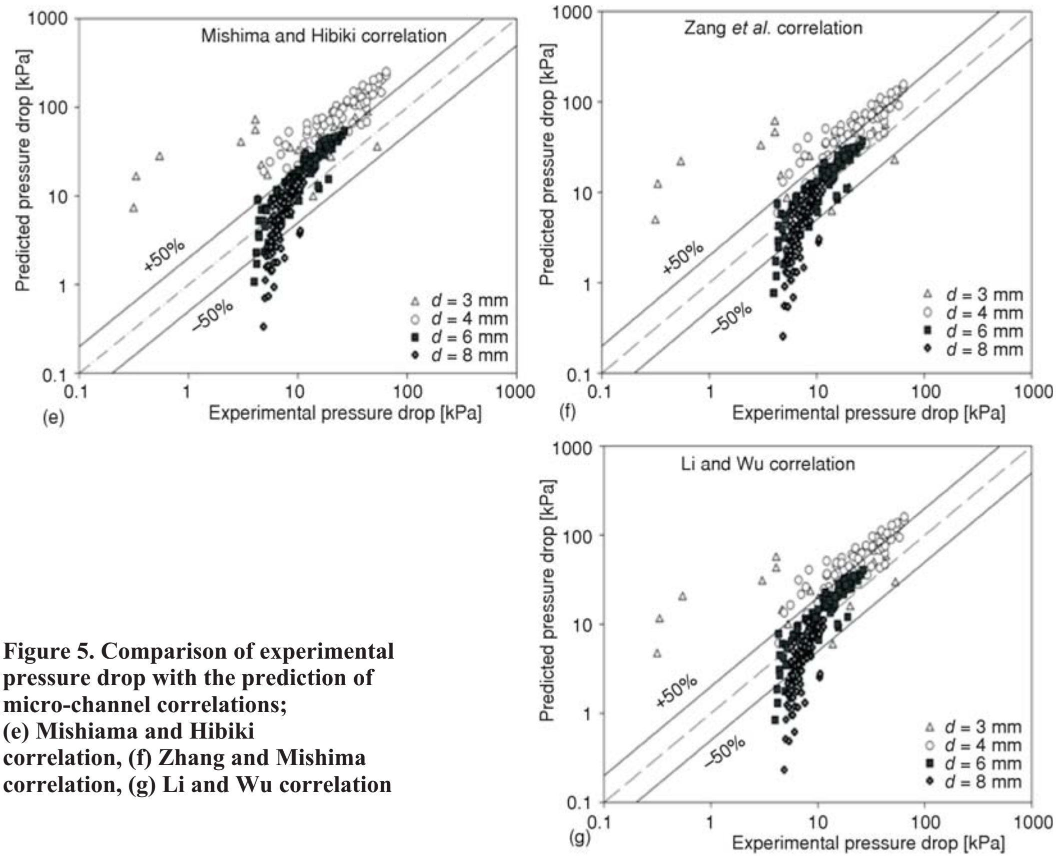

Figure 5. Comparison of experimental pressure drop with the prediction of micro-channel correlations; (e) Mishiama and Hibiki correlation, (f) Zhang and Mishima correlation, (g) Li and Wu correlation

Proposed correlation

In the present study, the predictive capability of the available two-phase flow pressure deop correlation for macro-channels and mini-channels were assessed. As per discussion in section 3.5, these correlations were found unsatisfactory. A new correlation is developed for better agreement with experimental observations.

The frictional resistance of the two-phase flow is expressed by the classical correlation developed by Lockhart-Martinelli [2]. Chisholm-Laid [8] proposed an analytical form of formulae for the calculation of the correction factors of two-phase flow resistance:

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

The value of ϕ_{l}^2 liquid correction factor depends on Martinelli parameter χ and flow characteristics of liquid and gas phase. Table 5 gives values for constant C for different flow regimes.The experimental ϕ_{l}^2 values are compared with that as predicted by Chisholm correction factor values.

Table 5. Values of *C* for different flow types as given by Chisholm and Laid [3]

Liquid	Gas	C
Turbulent	Turbulent	20
Laminar	Turbulent	12
Turbulent	Laminar	10
Laminar	Laminar	5

Figure 6 (a-d) presents the comparison of the calculated correction factor ϕ_{l}^2 ($C = 5$ and $C = 20$ – solid lines and $C = 10$ and $C = 12$ – dotted lines) and experimental correction factor ϕ_{l}^2 *vs.* Martinelli parameter χ. The results evaluated are compared with the experimental results of air-water two-phase flow mixture for 3.0, 4.0, 6.0, and 8.0 mm diameter tubes. Depending upon the flow condition of experimentation, these results characterized into two regimes. One regime is laminar flow of water and turbulent flow of air and other regime is turbulent

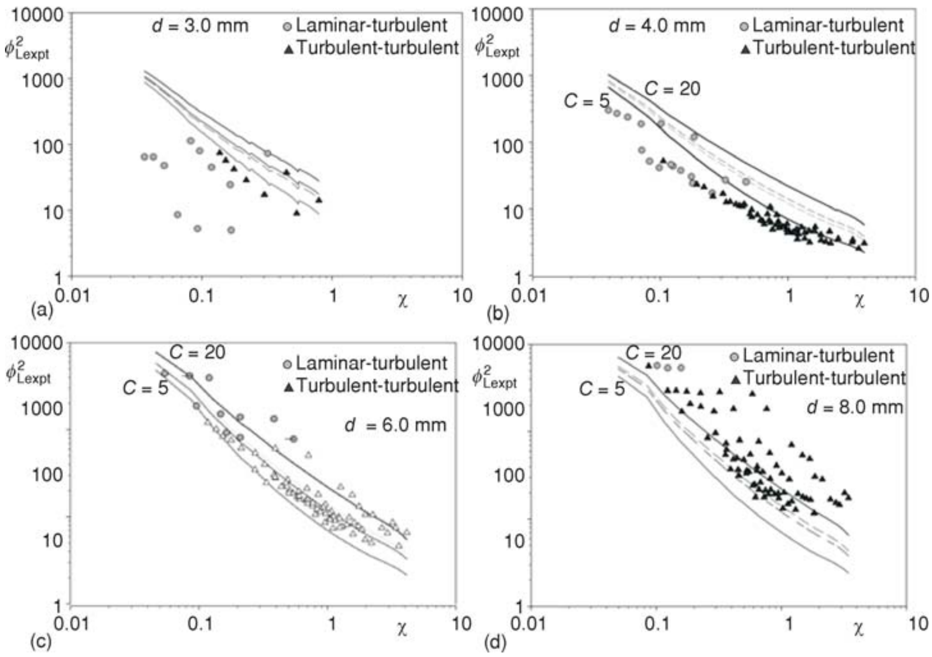

Figure 6. Comparison of the calculated correction factor ϕ_{L}^2 ($C = 5$ and $C = 20$ – solid lines) and experimental correction factor ϕ_{L}^2 *vs.* Martinelli parameter *x*; (a) *d* = 3.0 mm, (b) *d* = 4.0 mm (c) *d* = 6.0 mm, (d) *d* = 8.0 mm

flow of water and as well of air. It is necessary to investigate the influence of different parameters on the constant *C* for two-phase flow mixture in small diameter tubes.

Many investigators observed that there is influence of various parameters on the value of constant C. Mishima-Hibiki [5] proposed that value *C* depends on the mini-channels diameter. Li-Wu [7] concluded that Bond number and Reynolds number play important role in development of new correlation for modification of correction factor in mini-channels. Similar conclusions are made by Lee and Lee [9], Tran *et al*. [10], and Zang and Webb [11] based on flow regimes of phases.

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 mini-channels and beginning of macro-channels. Considering above discussed issues, it is decided to modify Chisholm correction factor of two-phase multiplier.

It is noted from the open literature that the surface tension force becomes an important parameter for hydraulic diameter less than 10.0 mm and dominate below 5.0 mm. The general agreement in the literature pertaining to two-phase flow in small diameter tubes that the surface tension has an increasing effect on the flow behavior and pressure drop as channel diameter decreases [13]. There is influence of surface tension in non-dimensional numbers such as Webber, and Bond number. Hence these are calculated over the range of all diameters experimental conditions of two-phase flow.

The high Froude number shows that the internal forces are significantly larger than the gravitational effects. 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.

Many other non-dimensional numbers are also investigated in the present study. These are calculated over the experimental range for all diameters. Few of them are mentioned with lowest and highest values in tab. 6.

Table 6. Range of non-dimensional numbers calculated over the experimental range for all test sections

Non-dimensional numbers	Fr	We	Bo	Re_l/Re_v
Range	74.34-95788400	82.84-1356.05	0.3025-3.26	0.0365-2.174

Multiple non-linear regression analysis was carried out to verify the effect of different non-dimensional numbers. After detail investigation, it has been found that *C* is function of ratio of Reynolds numbers of liquid phase to gas phase, quality of mixture and Froude number. Following expression is obtained using regression analysis:

$$C = 68.511\left[\left(\frac{\mathrm{Re}_L}{\mathrm{Re}_v}\right)^{0.9538}(x)^{-0.5016}(\mathrm{Fr})^{-1.2149}\right] \quad (2)$$

Standard regression analysis is carried out first set of statistical feature of regression is calculated and listed in tab.7. The multiple parameters *R* and R^2 are used to verify the developed regression model fit into the given data set.

Table 7. Validation of the regression analysis

Multiple *R*	0.9839
R square	0.9680
Adjusted *R* square	0.9676
Standard error	5.8348

Figure 7(a-e) shows that the comparison of experimental pressure drop with that as predicted by proposed model pressure drop for 3.0, 4.0, 6.0 and 8.0 mm diameter tubes, respectively. A close match can be observed between the predicted and experimental values. This correlation predicted the experimental data with mean average deviation 66%, 37%, 94%, and 87% for 3.0, 4.0, 6.0 and 8.0 mm diameter tubes, respectively.

Figure 7(e) shows the comparison of experimental pressure drop data as predicted by proposed correlation for two-phase flow of air-water in 3.0, 4.0, 6.0 and 8.0 mm diameter tubes on same graph. Proposed correlation predicts 66% data for 3.0 mm diameter tube within ±35%

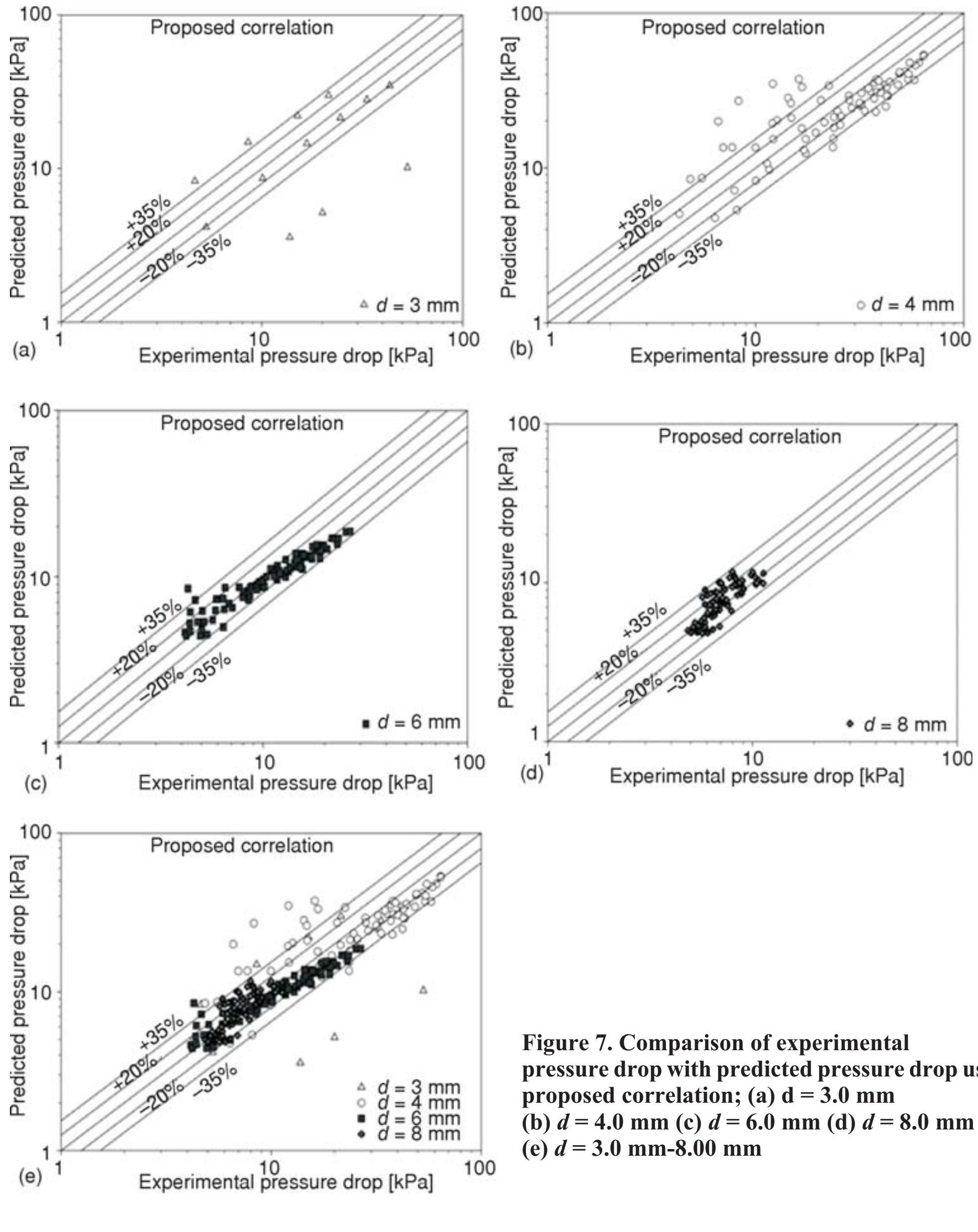

Figure 7. Comparison of experimental pressure drop with predicted pressure drop using proposed correlation; (a) d = 3.0 mm (b) *d* = 4.0 mm (c) *d* = 6.0 mm (d) *d* = 8.0 mm (e) *d* = 3.0 mm-8.00 mm

error band. Furthermore, it predicts 72% of data in 4.0 mm diameter tube within ±35% error band. For 6.0 and 8.0 mm diameters tubes, the results are predicted 94% and 87% within the ±35% error band.

Conclusions

An experimental set-up was designed and fabricated to conduct two-phase flow experiments. Two-phase pressure drop experiments were conducted with air-water mixture as working fluid. Based on 254 experimental data points analysis was carried out to characterize two-phase frictional pressure drop in small diameter tubes at horizontal orientation. The predictive capabilities of some of the macro channels and mini-channels existing corrections were assessed by comparing them with the experimental data. Based on the correlation of Lockhart-Martinelli [3] new correlation was proposed to analyze two-phase pressure drop in the small diameter tubes at horizontal orientation.

Major findings of performed investigation are as follows.

- The Chisholm correlation value of constant C in ϕ_L^2 correction factor is dependent upon the Martinelli parameter χ and flow characteristics of liquid and gas phases. The experimental value of C was not in the expected range.
- However, detail investigation was carried out to find out the influence of different flow parameters such as surface tension, quality, mass flux of liquid and gas, different dimensionless numbers such as Bond number, Weber number, Reynolds numbers for liquid and gas phase, Froude number, and dimensions of diameters of tube of two-phase flow.
- It was found that C value was strongly influenced by ratio of Reynolds numbers, Froude number and fallowed by quality of mixture.
- The Mishima-Hibiki [5], Zhang-Mishima [6], and Li-Wu [7] correlation shows close results to proposed correlation and can well predict the frictional pressure drop in 6.0 mm diameter tube followed by 8.0 mm diameter tube.
- Homogenous, Lockhart-Martinelli, Chisholm, and Friedel correlation are not predicted well the experimental two-phase flow pressure drop data of small diameter horizontal tubes.
- Based on experimental data, new correlation has been developed. This correlation was found to predict the experimental data satisfactory.

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Nomenclature

Bo – Bond number, $g(\rho_1 - \rho_g)D^2/\sigma$
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, $G^2(gD\rho_m^2)$
G – mass flux, [kgm^{-2}s^{-1}]
N – total number of data points
ΔP – pressure drop, [kPa]
We – Weber number ($G^2D/\sigma\rho_m$)
x – mass fraction, mass of air/mass of air + mass of water

Greek symbols

ϕ_l^2 – two-phase friction multiplier for liquid flowing alone
m – dynamic viscosity, [Nsm^{-2}]
ρ – density, [kgm^{-3}]
ρ_m – mixture density, [kgm^{-3}]
σ – surface tension of liquid (Nm^{-1})
χ – Martinelli parameter

Ω – chen correlation factor

Subscripts

g – gas phase only
l – liquid phase only
TP – two-phase

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