ON THE PREDICTION OF EXPERIMENTAL TWO-PHASE PRESSURE DROP THROUGH MICROCHANNELS

Charthankar Shantanu Babasaheb *[1], Autee Arun Tukaram[1]

[1] Department of Mechanical Engineering, Maharashtra Institute of Technology, Chhatrapati Sambhajinagar (Aurangabad), Maharashtra, India.

*Corresponding author; shantanubc@gmail.com; Coauthor: arun.autee@gmail.com

In many different industrial sectors, including power plants, petroleum refineries, and process industries, two-phase flow is an essential element. It is critical to anticipate the pressure drop in two-phase flow accurately which is dependent on number of factors, including the mass fluxes of the phases, the channel's orientation, cross section, and size. An experimental investigation of adiabatic two-phase air-water flow in microchannels is presented in this paper. Acrylic rectangular microchannel with hydraulic diameter (Dh) of 0.367, 0.411, 0.554 mm at horizontal orientation for the mass flux ranging from 290 to 1310 kgm^{-2}s^{-1} were used for conducting the experimental study. A few of the already known correlations were compared to the experimental two-phase pressure drop. Evaluation showed that the current correlations were insufficient to forecast the experimental findings. A new empirical correlation in terms of fluid characteristics and dimensionless numbers was developed based on the experimental results. The proposed correlation matches the current experimental results quite well. Most of the data was found to lie within the ± 25% error zone.

Key words: *Microchannels; Two-phase flow; Frictional pressure drop; Gas and liquid superficial velocity; Mean Absolute Error.*

1. Introduction

Two-phase flow in microchannels is critical for applications like electronic cooling, compact heat exchangers, and micro-propulsion systems. Fluid flow through small spaces, typical of microchannels, results in significant pressure drops compared to larger channels. Accurate prediction of pressure loss is essential for advancing micro-scale technologies. Enhanced pressure drops and fluctuations during flow boiling limit its broader application in heat exchange devices. Thus, understanding pressure drop and void fraction is vital, often requiring revaluation of macroscale fluid theories.

Microchannels are classified using parameters like hydraulic diameter (Dh). Kandlikar and Grande [1] defined flow channels based on rarefaction effects, while Mehendale *et al.* [2] emphasized heat exchanger design using Dh. Lockhart and Martinelli [3] introduced the χ-parameter which is the ratio of pressure gradients in the liquid to vapor phases. Researchers like Friedel [4], Jung and Radermacher [5], Akers *et al.* [6] and Chisholm [7] proposed correlations for frictional pressure drops, focusing on channel size, refrigerants, fluid properties, and flow patterns.

Experimental studies revealed deviations from classical predictions. Sur and Liu [8], Chung and Kawaji [9] and Pfund *et al.* [10] observed unique flow characteristics, pressure drop trends, and scaling effects in microchannels. Kim and Mudawar [11] used extensive datasets to refine models for two-phase pressure drop. Mala and Li [12] and Faraji *et al.* [13] studied material and geometry effects, with models incorporating artificial neural networks. Zhang *et al.* [14] and Sun and Mishima [15] proposed improved correlations, incorporating factors like surface wettability and mass flux.

In experimental setups, air-water mixtures [17] and other working fluids were tested. Judy and Maynes [18] identified material and geometry effects, while Lee and Lee [20] explored horizontal rectangular channels. Saisorn and Wongwises [21] analysed circular microchannels, and Charthankar and Autee [22] studied mini channels with varying diameters, highlighting the link between tube diameter, flow rate, and pressure drop.

From August 2023 to January 2024, experiments were conducted at Lab 303, Mechanical Engineering Department, MIT, Chh.Sambhajinagar. A rectangular acrylic microchannel (Dh= 0.367, 0.410, 0.554 mm; length = 100 mm) was analysed in a horizontal orientation under adiabatic conditions. The observed data were compared against literature correlations. A generalized correlation was developed to predict experimental pressure drops.

The previous work [17] of one of the authors was published in "Thermal Science" covers experiments with Macro channel (with different bend angle and different orientations). The present study contributes to understanding two-phase pressure drops in microchannels, crucial for designing compact heat exchangers and HVAC systems. Existing methods for pressure drop estimation may vary significantly, underlining the need for precise modelling and experimentation.

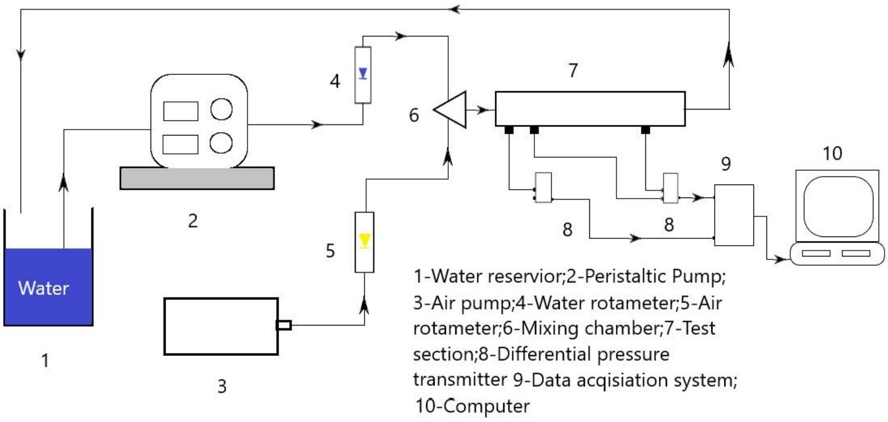
2. Experimental apparatus and procedure

The experiments were carried out using the setup as shown in Fig. 1. The details of the experimental facility are described as follows. Figure 1 illustrates a schematic diagram of the test facility. Air and water are used as working fluids in the system. The test sections were designed to be mounted on a table in a horizontal posture. A specially designed peristaltic pump sends water to the test area from the 2-liter tank. A control knob is used to adjust the water flow rate. An air pump provides atmospheric pressure air. A water rotameter with a range of 0 to 9 mLPM is used to supply water, while an air rotameter with a range of 0 to 1.5 LPM is used to supply air. The air flow rate was 0.75 lpm to 0.95 lpm while the water flow rate was 0.0032 lpm to 0.007 lpm. The test section is exposed to a two-phase flow mixture of water and air at room temperature that has been combined in a mixing chamber at varying flow rates. Through an exit tube, the test portion releases the air-water mixture into an open reservoir. Differential pressure transducers (DPT) with a 0-2.5 bar measuring range are used to quantify the two-phase frictional pressure drop. Table 1 shows uncertainties of the measuring instruments.

Table 1. Uncertainty of the measuring instruments

Instrument	Uncertainty (%)
Air Rota meter (0 to 1.5 LPM)	2
Water Rota meter (0 to 9 mLPM)	2
DPT 1 (0-2.5 bar)	5.16
DPT 2 (0-2.5 bar)	5.51

The experimental data is collected into a data gathering system that has been carefully designed. A computer records the experimental data that comes from the data acquisition equipment. During the experiment, rectangular microchannels with hydraulic diameter (Dh) of 0.367 mm (height 0.377 mm and width 0.358 mm) ,0.410 mm (height 0.415 mm and width 0.407 mm), 0.554 mm (height 0.588 mm and width 0.524 mm) and length of 100 mm were used. Every channel underwent the same experimentation process, and the outcomes were noted.



(a)

(b)

Fig. 1. Experimental Set up (a) Schematic View (b) Pictorial view of experimental apparatus

The frictional pressure drop of a two-phase air-water combination is studied in this study at various flow rates. To avoid water and air back pressurizing on measurement devices after mixing, the mixing chamber's design is essential. A specially designed mixing chamber as shown in Fig. 2 is used. Both sides of the mixing chamber open at a 45-degree angle to the air and water, which exits the center of the mixing chamber as a two-phase mixture. There is no back pressure effect on the measurement equipment as the water and air flows combine and flow smoothly in the same direction within the chamber.

Tests of single-phase pressure loss are conducted to verify the instruments and experimental setup. A rectangular channel test section measuring 100 mm in length and with a Dh of 0.367 mm

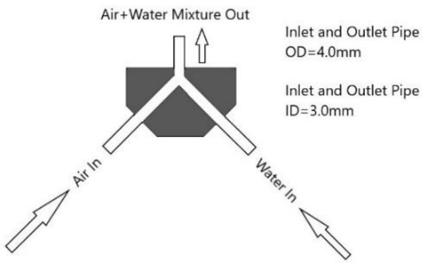


Fig. 2. Mixing Chamber

was used for the experiments. The operating fluid is water. It was noted how much the experimental pressure dropped with water flow. The measured friction factor f and the anticipated values of the Blasius correlation are compared in Fig. 3. It is noted that the experimental values and the Blasius correlation coincide well.

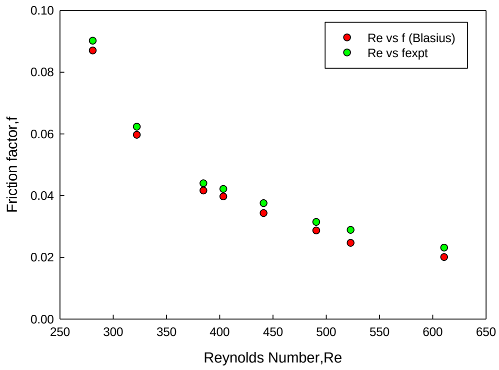


Fig. 3. Friction factor Vs Reynolds Number

Table 2. The MAE of the assessed correlation

Authors	MAE of the assessed correlation (%)	Correlations
Lockhart-Martinelli [3]	128.43	$\left(\frac{dp}{dz}\right)=\phi_L^2\left(\frac{dp}{dz}\right)_l=\phi_G^2\left(\frac{dp}{dz}\right)_g$, $\left(\frac{dp}{dz}\right)_l=\frac{2f_lG^2(1-x)^2}{\rho_lD}$, $\left(\frac{dp}{dz}\right)_g=\frac{2f_gG^2x^2}{\rho_gD}$ $\varphi_L^2=1+\frac{C}{X}+\frac{1}{X^2}$, $\mathrm{Re}_G=\frac{(Gx)D}{\mu_g}$ $\phi_G^2=1+CX+X^2$, $X^2=\frac{(dp/dz)_l}{(dp/dz)_g}$ $\mathrm{Re}_L=\frac{[G(1-x)]D}{\mu_l}$,
Chisholm [7]	166.56	$\phi_L^2=1+(X^2-1)\left[Bx^{0.875}(1-x)^{0.875}+x^{1.75}\right]$, $X^2=\frac{\left(\frac{dp}{dz}\right)_{go}}{\left(\frac{dp}{dz}\right)_{lo}}$

Friedel [8]	256.97	$\left(\frac{dp}{dz}\right)_{TP} = \phi_L^2 \left(\frac{dp}{dz}\right)_{lo}$, $\phi_L^2 = E + \frac{3.24FH}{F_r^{0.045} W_e^{0.035}}$, $F_r = \frac{G^2}{gD\rho_H^2}$, $W_e = \frac{G^2 D}{\sigma\rho_H}$, $E = (1-x)^2 + x^2 \frac{\rho_l f_{vo}}{\rho_{vo} f_l}$, $F = x^{0.78}(1-x)^{0.224}$, $H = \left(\frac{\rho_l}{\rho_v}\right)^{0.91} \left(\frac{\rho_v}{\rho_l}\right)^{0.19} \left(1-\frac{\rho_v}{\rho_l}\right)^{0.7}$
Mishima Hibiki [23]	55.76	$\left(\frac{dp}{dz}\right)_F = \left(\frac{dp}{dz}\right)_f \varphi_f^2$; $\varphi_f^2 = 1 + \frac{C}{X} + \frac{1}{X^2}$ For rectangular channels: - C= 21[1-exp(-0.319D_h)]; D_h(mm) For circular tubes: - C= 21[1-exp(-0.333D)]; D(mm)
Lee and Lee [20]	68.47	$C = A\lambda^q \psi^r \mathrm{Re}_{lo}^s$, $\lambda = \frac{\mu_l^2}{\rho_l \sigma D}$, $j_G = \frac{Gx}{\rho_G}$, $\psi = \frac{\mu_l j_G}{\sigma}$
Qu-Mudawar [24]	100.31	Using Lockhart and Martinelli correlation, $C_{Q\&M}$= 21[1-exp(-0.319D_h)] (0.00418G + 0.0613)
Zhang *et al.* [25]	181.01	Using Lockhart and Martinelli correlation, C_{Zhang} = C= 21[1-exp(-0.358/La)]
Chen *et al.* [26]	49.18	$\left(\frac{dp}{dz}\right) = \left(\frac{dp}{dz}\right)_{\mathrm{hom}} \Omega_{\mathrm{hom}}$, $Bo = g(\rho_l - \rho_g)\frac{(D/2)^2}{\sigma}$, $\Omega_{\mathrm{hom}} = \begin{cases} 1 + (0.2 - 0.9e^{-Bo}), & For\ Bo < 2.5 \\ 1 + \left(\frac{W_e^{0.2}}{[e^{Bo}]^{0.3}}\right) - 0.9e^{-Bo}, & For\ Bo \geq 2.5 \end{cases}$, $W_e = \frac{G^2 D}{\sigma\rho_H}$

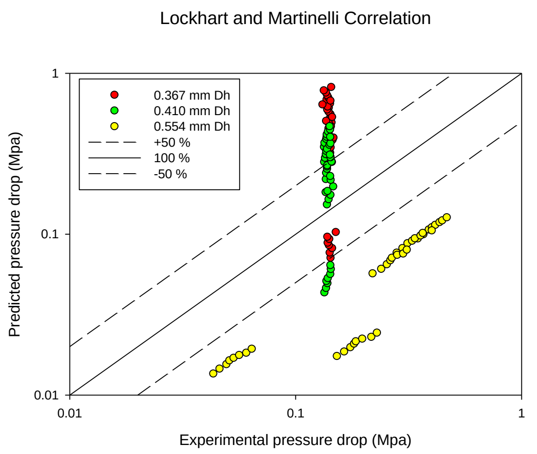
3. Results and Discussion

To assess the two-phase frictional pressure drop for a mixture of air and water moving through a horizontal microchannel, the obtained experimental data is statistically analyzed. Figure 4 compares the experimental two-phase frictional pressure drop to the values anticipated by the pressure drop calculation. The ordinate shows the expected pressure decrease, while the abscissa represents the experimental pressure drop.

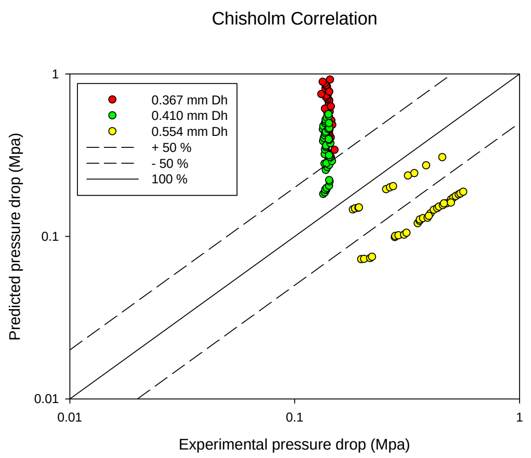
The mean absolute error (MAE), which is defined as the measure of the precision of correlations, is given by the following Eq.

$$MAE = \frac{1}{N}\sum\frac{\left|\Delta P_{Pred} - \Delta P_{Expt}\right|}{\Delta P_{Expt}} \times 100\ \% \tag{1}$$

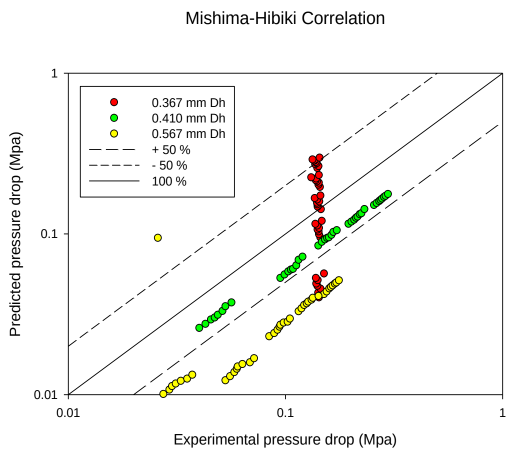
Figure 4 and Tab. 2 reveal that most of the models overpredict the two-phase frictional pressure drop compared to the experimental values. Suwankamnerd and Wongwises conducted experiments with two-phase air–water flow in a single rectangular copper microchannel with a hydraulic diameter of 267 μm and predicted the pressure drop by homogeneous flow model and the Friedel correlation separated flow model [27]. The Lockhart-Martinelli model, frequently used for macro-channels, lacks consistency for predicting experimental results.



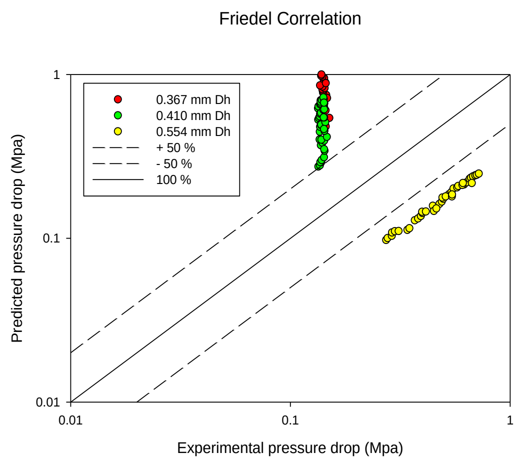
(a)



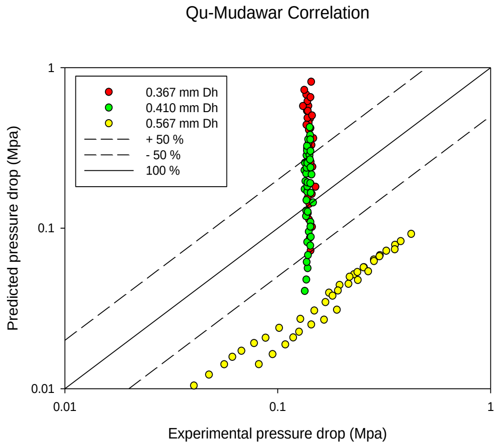
(b)



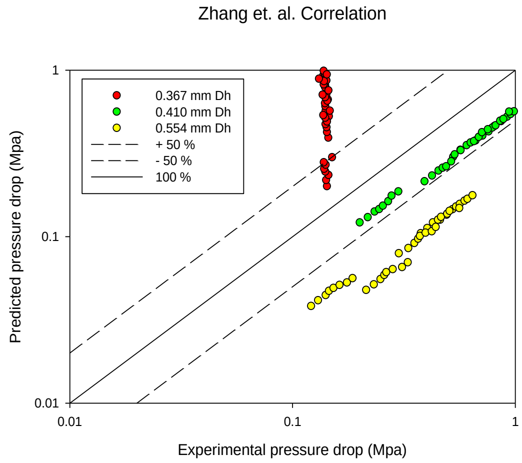
(c)



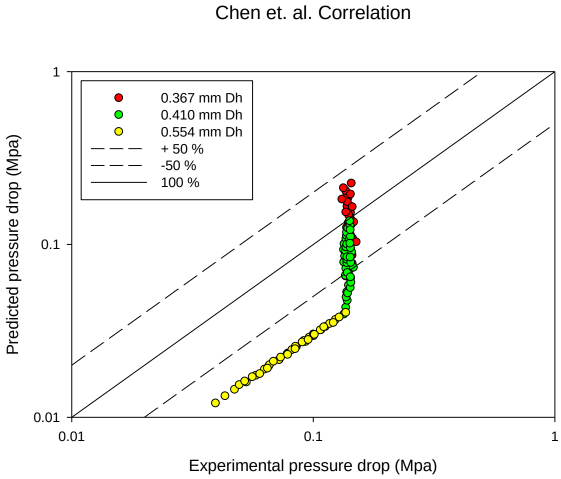
(d)



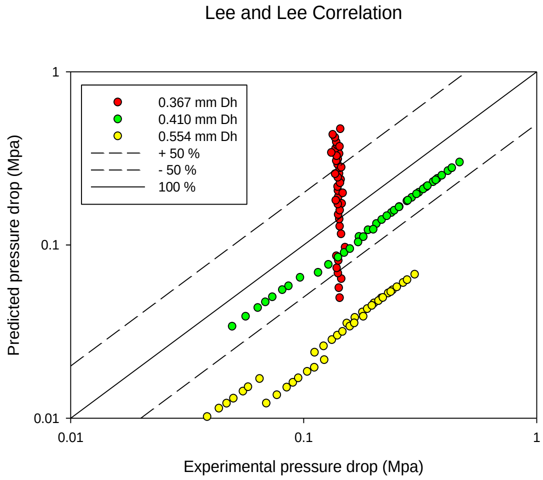
(e)



(f)



(g)



(h)

Fig. 4. Comparison of experimental frictional pressure drop values with the predicted pressure drop values of for (a) Lockhart-Martinelli, (b) Chisholm, (c) Friedel, (d) Mishima-Hibiki (e) Qu-Mudawar, (f) Zhang *et al.*, (g) Chen, (h) Lee and Lee correlations

It is less applicable to small-size channels because of the impact of surface and size in microchannels. As presented in Fig.4(a), the Lockhart-Martinelli model predicted the experimental results with MAE of 128.43%. The correlation of Friedel overestimated the experimental pressure drop with MAE of 256.97 % is shown in Fig. 4(b), and the Chisholm model inaccurately predicts the experimental data with 166.56 % MAE as shown in Fig. 4(c). The correlations proposed by Mishima-Hibiki, Qu-Mudawar, Zhang *et.al.*, Chen, Lee and Lee as represented in Fig. 4(d, e, f, g and h) respectively. It is clear that Chen and Mishima-Hibiki correlations yielded close agreement with the experimental data with MAE of 49.18 % and 55.76 % respectively, whereas Qu-Mudawar, Zhang *et al.*, Chen, Lee and Lee correlations either overpredict or underpredict the experimental data with MAE of 100.31 %,181.01 % and 68.47 % respectively. The predictability of Chen and Mishima-Hibiki correlations is better as compared with other correlations considered for the study. In Chen correlation, the effect of surface tension is considered for small diameter tubes/channels while in the Mishima-Hibiki correlation, the effects of hydraulic diameter on experimental pressure drop are reflected. Along with hydraulic diameter, the Qu-Mudawar correlation had counted the effect of total maas flux.

But in the case of Lee and Lee correlation the superficial velocity of gas is also considered. Table 3 shows detailed information about the compared correlation.

Table 3. Detailed information about the compared correlation

Correlation	Fluids	Geometry	Orientation	Diameter	Adiabatic or not
Lockhart-Martinelli [3]	Water, Oil, Hydrocarbon	Circular	Horizontal	Dh=1.49 to 25.83 mm	Adiabatic
Chisholm [7]	In this paper Eq. for the prediction of local friction pressure gradients during the turbulent flow of two-phase mixtures have been developed in a form which permits their ready integration to give the overall pressure drop during evaporation.				
Friedel [8]	Air-water, Air-Oil, R12	Circular tubes	Horizontal and vertical	D> 4 mm	Adiabatic
Mishima Hibiki [23]	Air-water	Capillary Tubes	Vertical	D=1.05-4.08 mm	Adiabatic
Lee and Lee [20]	Air-water	Rectangular	Horizontal	Dh=0.78 to 6.67 mm	Adiabatic
Qu-Mudawar [24]	Deionized Water	Rectangular	Horizontal	Width 231µm and Depth 712 µm	Non adiabatic
Zhang *et al.* [25]	Air/N_2-water, Air/Ethanol, Ammonia, Refrigerants, Water	Circular and Rectangular mini and micro-channels	Horizontal and Vertical	Dh=0.07 to 6.25 mm	Adiabatic
Chen *et al.* [26]	Air-water, R410A, Ammonia	Circular	Horizontal	D=1.02 to 9.00 mm	Adiabatic

3.1. Proposed correlation

The experimental measurements were performed to obtain a reliable and accurate correlation for two-phase flow in microchannels using air and water as working fluids. The purpose of these measurements was to study two phase flow pressure drop, create predictive models, validate and benchmark the results, and confirm the correlation's relevance for diverse practical and industrial applications, especially those involving air-water systems.

The current study evaluated the existing two-phase flow pressure correlation's predictive capacity for macro-, mini- and microchannels. The discussion in this section indicates that these connections were deemed inadequate. To improve agreement with experimental observations, a new correlation is created. Lockhart-Martinelli's classical correlation expresses the frictional resistance of the two-phase flow. An analytical version of the following formulas, presented by Chisholm, can be used to determine the two-phase flow resistance correction factors:

$$\varphi_L^2 = 1 + \frac{C}{X} + \frac{1}{X^2} \quad (2)$$

The Chisholm parameter "C" in the Lockhart-Marinelli correlation was solely represented as a function of the liquid and gas flow characteristics. The liquid and gas phase flow characteristics as well as the parameter C determine the value of the φ_L^2 liquid correction factor. Previous experimental studies of Sun and Mishima [15], Lee and Lee [20], Mishima and Hibiki [23] and Venkatesan *et al.* [28] have proposed that at smaller diameters, the Chisholm parameter "C" is dependent on surface tension and other flow parameters. Therefore, a modified correlation for this Chisholm parameter "C" is constructed in the current study. The values of the Chisholm correction factor are used to compare the experimental φ_L^2 values with the anticipated values. Based on phenomenological modelling, it was thought reasonable to invoke the correlation for the Chisholm parameter "C." Physically, bubbles are compressed in the flow channel as the hydraulic diameter decreases, and surface tension eventually takes over the flow. Furthermore, the surface velocities of the phases also affect the two-phase frictional pressure drop. Thus, gravitational, surface tension, viscous, and inertia forces all have an impact on the physical phenomenon of two-phase pressure drop. To enable a broader application of the developed correlations, these four forces are represented by distinct dimensionless numbers.

In the current study, numerous other non-dimensional numbers are also examined. These are computed for all diameters over the experimental range. Different non-dimensional numbers were tested for their impact using multiple non-linear regression analysis. The Reynolds number gives a measure of the ratio of inertia forces to viscous forces and consequently quantifies the relative importance of these two forces for the 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 dominant, while turbulent flow occurs at high Reynolds numbers and is dominated by inertia forces. As the mass flux of liquid and gas increases, there is increased interaction between the fluids and the inertia force dominates. This effect increases the frictional pressure drop further as the diameter of tube decreases. A key factor in comprehending and forecasting the behaviour of two-phase fluid flow in microchannels is the Weber number (We). It gives significance of surface tension forces to inertia forces. In microchannels, due to small characteristic lengths, surface tension effects are significant, so the Weber number is crucial for predicting whether the flow will remain stable or be disrupted by inertial effects.

It was observed that C depends on the Weber number, and gas phase Reynolds numbers, Two-phase Reynolds number, and Gas superficial velocity. To investigate the influence of different parameters on the Chisholm parameter ‘C’ and to develop a correlation for ‘C’ as a function of different dimensionless numbers, regression analysis was carried out with the help of the present experimental data base of 239 points. Half of the data were used for the development of the new correlation while the remaining half of the data were used for validating the developed correlation. Multiple regression analysis is used to get the following expression:

$$C = 12 * Re_{go}^{-0.75} * \left\{1 - \left[\left(Re_{tp}^{-1.53988}\right) * \left(\frac{We_{tp}^{0.61509}}{J_g^{-1.99489}}\right)\right]\right\} \quad (3)$$

The first step in standard regression analysis is to calculate the statistical characteristics of the regression which are mentioned here. The values of parameters R and R^2 are 0.9808 and 0.9619, respectively, to ensure that the developed regression model matches the given data set.

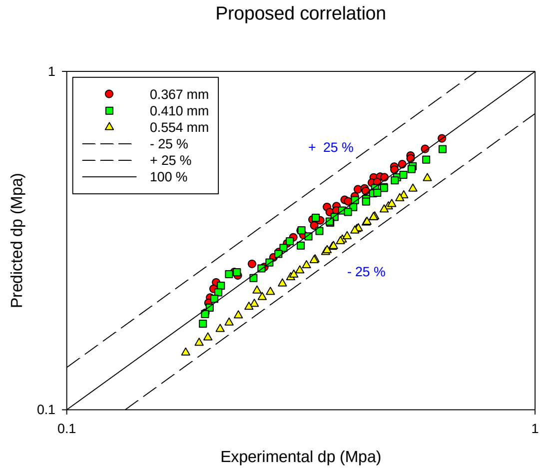


Fig. 5. Comparison of experimental frictional pressure drop values with the predicted pressure drop of proposed correlation

The comparison of present experimental pressure drop data as predicted by the proposed correlation for two-phase frictional pressure drop for a mixture of air and water moving through horizontal microchannels with the hydraulic diameters of 0.367,0.410 and 0.567 mm is displayed in Fig. 5. 100 % of the data for 0.367, 0.410 and 0.567-mm hydraulic diameter microchannel predicted by the proposed correlation is within ~25%.

4. Conclusions

Two-phase flow experiments were planned and carried out using an experimental setup that was created. Studies on two-phase pressure drops were carried out using a mixture of air and water as the working fluid. Analysis was done to characterize the two-phase frictional pressure drop in rectangular microchannels at horizontal orientation based on experimental data. By contrasting the known corrections for the mini and micro channels with the experimental data, their predictive power was evaluated. A novel correlation was put out to analyze the two-phase pressure drop in rectangular microchannels at horizontal orientation, based on the correlation between the Lockhart-Martinelli and Chisholm parameter. The newly developed correlation has significant potential in in the field of refrigeration capillary and other applications and especially in academic and industrial research due to its ability to predict pressure drops, accurately. In future, modelling and simulation of the experimental results are planned. Major findings of the experimental investigation are as follows: -

1.With MAE values of 49.18% and 55.76%, the Chen and Mishima-Hibiki correlations produced results that were in close agreement with the experimental data.

2. The experimental two-phase flow pressure drop data of a rectangular microchannel in horizontal orientation cannot be accurately predicted by the correlations put forth by Qu-Mudawar, Zhang et al., Lee and Lee, Lockhart-Martinelli, Chisholm, and Friedel.

3. A new correlation has been established using data from experiments. Within the ± 25% error zone, this correlation was found to satisfactorily predict the present experimental data.

Nomenclature

A	Cross section (m^2)	ρ	Density (kgm^{-3})

C	Chisholm parameter	σ	Surface tension (Nm^{-1})
Dh	Characteristics Diameter (m)	Ω	Correction factor
Δp	Pressure drop (MPa)	λ	Dimensionless parameter showing relative importance of viscous and surface tension effects in Lee and Lee correlation.
g	Gravitational acceleration (ms^{-2})	Ψ	Dimensionless parameter showing relative importance of velocity of liquid slug in Lee and Lee correlation
j	Superficial velocity (ms^{-1})	χ	Lockhart–Martinelli parameter
m	Mass flow rate (kgs^{-1})	ϕ	Two-phase frictional multiplier
Re	Reynolds number	f	Friction factor
We	Weber number	μ	Dynamic viscosity (Nsm^{-2})
G	Mass flux ($kgm^{-2}s^{-1}$)		**Subscripts**
E	Parameter in Friedel correlation for two-phase pressure drop	a	Acceleration
F	Parameter in Friedel correlation for two-phase pressure drop	v	Gas phase only
X	Mass fraction of gas in two-phase mixture (vapor quality)	go	All mass is assumed as gas only
H	Parameter in Friedel correlation	H	Hydrostatic
dp/dz	Pressure drop (MPa)	l	Liquid
N	Number of data points	lo	All mass is assumed as liquid only
Re	Reynolds Number	HOM	Homogeneous
Wb	Weber Number	TP	Two-phase
MAE	Mean Absolute Error	TPF	Two-phase Frictional
HVAC	Heating, Ventilation and Air conditioning	Pred	Predicted
	Greek Symbols	Expt	Experimental
ν	Kinematic viscosity (m^2s^{-1})		

References

[1] Kandlikar, S. G., Grande, W. J., Evolution of Microchannel Flow Passages-Thermohydraulic Performance and Fabrication Technology, *Heat Transfer Engineering*, *24* (2003), 1, pp. 3-17, DOI: 10.1080/01457630304040.

[2] Mehendale, S. S., *et.al.*, Fluid Flow and Heat Transfer at Micro- and Meso-Scales with Application to Heat Exchanger Design, *ASME Applied Mechanics Review, 53* (2000), 7, pp. 175–193, https://doi.org/10.1115/1.3097347.

[3] Lockhart, R. W., Martinelli, R. C., Proposed Correlation of Data for Equal Two-Phase, Two-Component Flow in Pipes, *Chemical Engineering Progress*, *45* (1949), 1, pp. 39-48

[4] Friedel, L., Improved Friction Pressure Drop Correlations for Horizontal and Vertical Two-Phase Flow, *Proceedings of European Two-Phase Flow Group Meeting,* Ispra, Italy, (1979)

[5] Jung, D. S., Radermacher, R., Prediction of pressure drop during horizontal annular flow boiling of pure and mixed refrigerants, *International Journal of Heat and Mass Transfer, 32* (1989), 12, pp. 2435-2446

[6] Akers, W. W., *et.al.*, Condensation heat transfer within horizontal tube, *Chemical Engineering Progress Symposium Series*, *55* (1959), 29, pp. 171-176

[7] Chisholm, D., Pressure Gradients due to Friction during the Flow of Evaporating Two-Phase Mixtures in Smooth Tubes and Channels, *International Journal Heat Mass Transfer, 16* (1973), 2, pp. 347-358

[8] Sur, A., Liu, D., Adiabatic air-water two- phase flow in circular micro channels, *International Journal of Thermal Sciences, 53* (2012), pp. 18-34

[9] Chung, P. M. Y., Kawaji, M., The effect of channel diameter on adiabatic two-phase flow characteristics in microchannels, *International Journal of Multiphase Flow, 30* (2004), 7-8, pp. 735–761

[10] Pfund, D., *et.al.*, Pressure drop measurements in a microchannel, *AIChE Journal, 46,* (2000), 8, pp. 1496–1507

[11] Kim, S. M., Mudawar, I., Universal approach to predicting two-phase frictional pressure drop for adiabatic and condensing mini/micro-channel flows, *International Journal of Heat and Mass Transfer, 55* (2012), 11-12, pp. 3246-3261

[12] Mala, Gh. M., Li, D., Flow characteristics of water in microtubes, *International Journal of Heat and Fluid Flow, 20* (1999), 2, pp. 142-148

[13] Faraji, F., *et.al.*, Two-phase flow pressure drop modelling in horizontal pipes with different diameters, *Nuclear Engineering and Design, 395* (2022), 111863

[14] Zhang, Y., *et.al.*, Flow Pattern Study and Pressure Drop Prediction of Two-Phase Boiling Process in Different Surface Wettability Microchannel, *Micromachines*, *14* (2023), 5, 958, https:// doi.org/10.3390/mi14050958.

[15] Sun, L., Mishima, K., Evaluation Analysis of Prediction Methods for Two-Phase Flow Pressure Drop in Mini-Channels, *International Journal of Multiphase Flow, 35* (2009), 1, pp. 47-54

[16] Schmid, D., *et.al.*, Adiabatic two-phase pressure drops of carbon dioxide in different channel orientations, *International Journal of Heat and Fluid Flow, 95* (2022), 108966

[17] Autee, A., *et al.*, Experimental Study on Two-Phase Pressure Drop of Air-Water in Small Diameter Tubes at Horizontal Orientation, *Thermal Science, 18* (2014), 2, pp. 521-532

[18] Judy, J., Maynes, D., Characterization of frictional pressure drop for liquid flows through microchannels, *International Journal of Heat and Mass Transfer, 45* (2002), 17, pp. 3477-3489

[19] Autee, A. T., Giri, S. V., Experimental study on two-phase flow pressure drop in small diameter bends, *Perspectives in Science, 8* (2016), pp. 621-625

[20] Lee, H. J., Lee, S. Y., Pressure drop correlations for two-phase flow within horizontal rectangular channels with small heights, *International Journal of Multiphase Flow, 27* (2001), 5, pp. 783-796

[21] Saisorn, S., Wongwises, S., The effects of channel diameter on flow pattern, void fraction and pressure drop of two-phase air–water flow in circular micro-channels, Experimental Thermal and Fluid Science, 34 (2010), 4, pp. 454-462

[22] Charthankar, S.B., Autee, A.T., Experimental Studies on the Two-Phase Pressure Drop Through Minichannels, In: Narasimhan, N.L., Bourouis, M., Raghavan, V. (eds), Recent Advances in Energy Technologies, Lecture Notes in Mechanical Engineering, Springer, Singapore, (2023), pp. 259–271

[23] Mishima, K., Hibiki, T., Some characteristics of air-water two-phase flow in small diameter vertical tubes, *International Journal of Multiphase Flow, 22* (1996), 4, pp. 703–712

[24] Qu, W., Mudawar, I., Measurement and prediction of pressure drop-in two-phase micro-channel heat sinks, *International Journal of Heat and Mass Transfer, 46* (2003), 15, pp. 2737-2753

[25] Zhang, W., *et.al.*, Correlations of two-phase frictional pressure drop and void fraction in mini channel, *International Journal of Heat and Mass Transfer, 53* (2010), 1-3, pp. 453-465

[26] Chen, Y., *et.al.*, Two-phase pressure drop of air–water and R-410A in small horizontal tubes, *International Journal of Multiphase Flow, 27* (2001), 7, pp. 1293-1299

[27] Suwankamnerd, P., Wongwises, S., An experimental study of two-phase air-water flow and heat transfer characteristics of segmented flow in a microchannel, *Experimental Thermal and Fluid Science*, *62* (2015), pp. 29-39

[28] Venkatesan, M., *et.al.*, Effect of diameter on two-phase pressure drop in narrow tubes, *Experimental Thermal and Fluid Science, 35 (*2011), pp. 531-542

Submitetd: 03.10.2024.
Revised: 03.01.2025.
Accepted: 10.01.2025.