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EXPERIMENTAL INVESTIGATION AND PERFORMANCE EVALUATION OF ISOTHERMAL FRICTIONAL TWO PHASE PRESSURE DROP CORRELATIONS IN VERTICAL DOWNWARD GAS-LIQUID TWO PHASE FLOW

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ABSTRACT

The correct prediction of gas-liquid two phase pressure drop is of immense significance for proper sizing of industrial equipment and safety operations involved in chemical, energy and petrochemical applications. The hydrostatic component of the two phase pressure drop is predicted based on the accurate estimation of void fraction. However, there exists a complexity in correct estimation of the frictional component of two phase pressure drop owing to interfacial friction at dynamic gas-liquid interface. The present study is focused on the experimental measurements of gas-liquid two phase frictional pressure drop and the performance evaluation of eleven correlations for its prediction in vertical downward orientation. The experimental determination of two phase frictional pressure drop is carried out for a 0.01252 m I.D. pipe with surface roughness of 0.0000152 m using air-water as the fluid combination. Unlike most of the other studies centered towards annular flow, this experimental study is spanned over different flow patterns and the entire range of the void fraction. In addition to the experimental measurements, the scope of this study also includes the performance analysis of eleven frictional pressure drop correlations available in the literature. These correlations are those based on the separated flow model initially proposed by Lockhart and Martinelli [1].The available frictional pressure drop correlations are compared against the data measured in the present study. Based on the experimental data available in the literature, the influence of the pipe diameter and fluid viscosity on the frictional pressure drop is also analyzed.

INTRODUCTION

The pressure drop in gas liquid two phase flow is a key parameter in designing and sizing of industrial equipment and components pertaining to the petroleum, chemical, refrigeration and nuclear industries. The knowledge of two phase flow void fraction and pressure drop is of significant importance in artificial gas lift systems. The understanding of two phase pressure drop is desired in the designing of the direct expansion ground source heat pumps systems and sizing of other refrigeration units. Nuclear engineering safety operations involving natural circulation loops also require a method of determining the two phase pressure drop. The two phase pressure drop consists of the hydrostatic, accelerational and frictional components of the pressure drop. The hydrostatic component of two phase pressure drop comes into picture due to significant density differences between the gas and liquid phase and the influence of gravity potential. The hydrostatic component can be predicted with sufficient accuracy by the accurate prediction of the void fraction. The accelerational component of pressure drop is usually small and can be neglected in comparison to the hydrostatic and frictional component for small pipe lengths. However, it can be of significant magnitude in artificial gas lift systems and pipelines carrying oil and natural gas mixture over long distances. The frictional component of two phase pressure drop has been a subject of research for many years due to complexity involved in its prediction. This complexity is evolved due to dependence of frictional pressure drop on flow patterns, pipe geometry and fluid properties. Literature reports several frictional pressure drop correlations developed for determining frictional pressure drop categorized as those based on empirical formulations and those conceived from the concept of separated flow model introduced by Lockhart and Martinelli [1]. Correlations of Awad and Muzychka [2], Friedel [3] are based on the concept of separated flow model. Yamazaki and Yamaguchi [4] and Lau et al. [5] based their model on the concept of using a similar concept but defined two phase multiplier determined as a function of void fraction. These correlations can be further classified as flow pattern independent and flow pattern specific correlations. The present study is concerned with the frictional component of the total two phase pressure drop. In addition to the wall friction, the interfacial friction between the two phases due to the slippage also contributes to the two phase frictional pressure drop. Thus the contribution of the interfacial friction to the two phase frictional component increases with increasing slip velocity or alternatively as the flow pattern transits from bubbly to annular flow regime. In past few years lot of research has been done over the frictional pressure drop in annular flow regime and the contribution of interfacial friction. In this study, we present a discussion on variation of frictional pressure drop for different flow patterns and the influence of pipe diameter and fluid properties on it.

NOMENCLATURE

D	pipe diameter (m)
f	friction factor
g	acceleration due to gravity (m/s^2)
G	mixture flux (kg/ms^2)
L	pipe length (m)
ΔP	pressure drop (Pa)
Re	Reynolds number
S	slip velocity (m/s)
U	phase velocity (m/s)

Greek Symbols

α	void fraction
μ	dynamic viscosity (Pa-s)
ρ	phase density (kg/m^3)
ϕ	non-dimensional two phase frictional pressure drop
θ	pipe inclination (degrees)

Subscripts

a	accelerational component
f	frictional component
h	hydrostatic component
g	gas
l	liquid
m	mixture
s	superficial
t	total
tp	two-phase

EXPERIMENTAL SETUP

The experimental set up used for measuring frictional pressure drop as shown in Figure 1 consists of a 0.01252 m I.D. schedule 10 S steel pipe of roughness 0.0000152 m for pressure drop and heat transfer measurements and a 0.0126 m I.D. polycarbonate clear pipe for void fraction measurement. The water stored in a 55 Gallon tank is circulated by a Bell and Gosset (series 1535, model number 3445 D10) and filtered through an Aqua-Pure AP12-T purifier before it is passed through a ITT model BCF 4063 shell and tube heat exchanger. The water then flows through Emerson (Micro Motion Elite Series model number CMF 100) Coriolis mass flow meter and then allowed to mix with air in a static mixer. The water mass flow rate is controlled by a gate valve placed after the water mass flow meter. The gas phase is the compressed air supplied by Ingersoll Rand T-30 Model 2545. Compressed air is passed through a filter and regulator circuit before it is fetched to the mass flow meter. The air mass flow rate is controlled using a Parker needle valve (Model 6A-NLL-NE-SS-V) and then allowed to mix with water in the mixer.

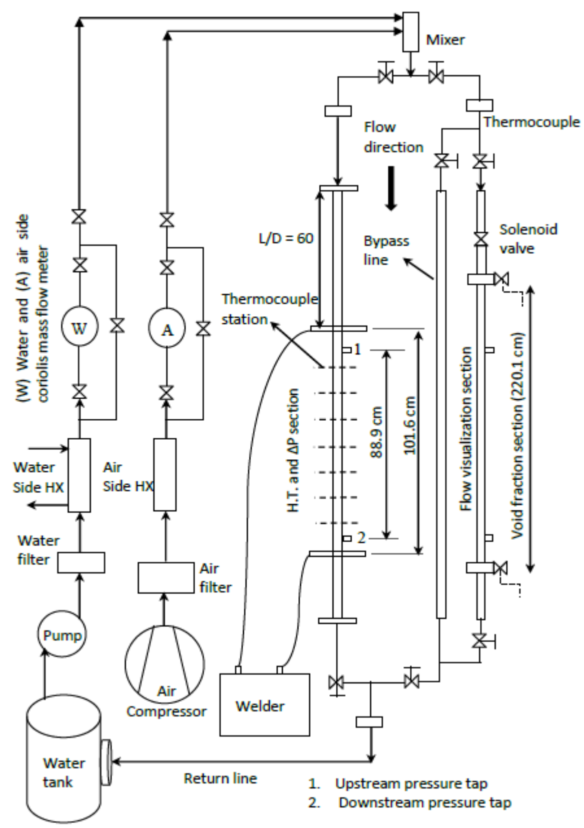

Figure 1 Schematic of experimental setup used in the present study for measuring frictional pressure drop.

The flow patterns were observed in the flow visualization section and the void fraction was measured using quick closing valves. The two phase pressure drop between the pressure taps 0.89 m apart was measured using the Validyne DP 15 pressure transducer and DP 26, DP 32 and DP 36 pressure diaphragms. The pressure transducer was calibrated every time the diaphragm was changed in addition to the occasional calibration to ensure repeatability. The differential pressure drop data was collected for 3-4 minutes at a sampling rate of 6000 samples per second to nullify any errors in the reading due to flow fluctuation. The average value of these samples over the measured period of time was considered to be representative of the measured values.

The total pressure drop per unit pipe length in two phase flow consists of hydrostatic, accelerational and frictional components represented as shown in Equation (1),

$$\left(\frac{\Delta P}{L}\right)_t = \left(\frac{\Delta P}{L}\right)_h + \left(\frac{\Delta P}{L}\right)_a + \left(\frac{\Delta P}{L}\right)_f \tag{1}$$

In the above equation the total pressure drop was determined experimentally by measuring the total pressure drop across the pipe by a pressure transducer. To determine the hydrostatic pressure drop in Equation (1), it was expressed in terms of mixture density (ρ_m) which is a function of void fraction (α) and liquid and gas densities (ρ_l and ρ_g) as shown in Equation (2),

$$\left(\frac{\Delta P}{L}\right)_h = \rho_m g \sin\theta = \left(\alpha\rho_g + (1-\alpha)\rho_l\right) g \sin\theta \tag{2}$$

The accelerational pressure drop in Equation (1) was negligible in the present study for isothermal air-water two phase flow since the flow pattern did not change along the pipe length and there was no phase change. The frictional component of the two phase pressure drop in Equation (1) is thus calculated based on the measured total pressure drop and the hydrostatic pressure drop as shown in Equation (3),

$$\left(\frac{\Delta P}{L}\right)_f = \left(\frac{\Delta P}{L}\right)_t - \rho_m g \sin\theta \tag{3}$$

The accuracy of the experimental setup was confirmed by the direct comparison between the experimentally measured friction factor (f) and that predicted by the correlations of Colebrook [6], Churchill [7] and Haaland [8]. As seen in Figure 2, the measured friction factor with an uncertainty of ±3.65% was found to be within ±5% of the values predicted by these correlations.

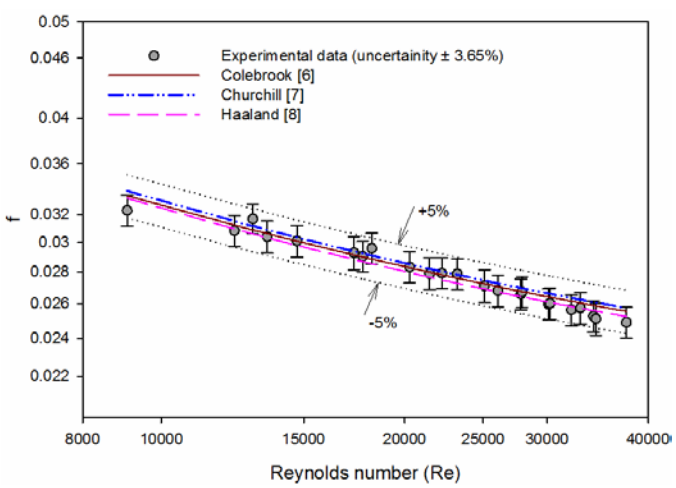

Figure 2 Comparison of experimentally measured and calculated single phase (water) friction factors.

The uncertainty associated with the measured frictional pressure drop for each flow pattern was determined using method of Kline and McClintock [9]. The uncertainty for each measured variable for a sample run and the corresponding uncertainty for the calculated variables, i.e. frictional pressure drop is shown in Table 1 while the minimum and maximum uncertainty for each flow pattern observed in the present study is reported in Table 2.

Table 1 Uncertainty of measured variables.

Parameter	Value	Uncertainty	% Uncertainty
ρ_l	997.2 kg/m^3	±0.6 kg/m^3	±0.06%
ρ_g	1.53 kg/m^3	±0.0009 kg/m^3	±0.058%
α	0.467	±0.0089	±1.9%
ΔP (meas)	-3771 Pa	±35 Pa	±0.25% F.S.
ΔP (fric.)	1447 Pa	±94.17 Pa	±6.5%

Table 2 Percentage of uncertainty in calculation of frictional pressure drop (Pa/m) for different flow patterns.

Flow pattern	Min.	Max.
Bubbly	1.95	9.4
Slug	2.57	10.47
Froth	2.63	1.26
Falling Film	2.84	5.57
Annular	1.02	3.78

The uncertainty in the bubbly and slug flow is primarily due to the large uncertainty associated with the void fraction in comparison to other flow patterns. However, it was observed that for more than 88% and 81% of data points in the bubbly and slug flow regimes respectively, the uncertainty was within ±6%. In addition to this, particularly for the slug flow the pressure drop measurements were difficult due to pulsating nature of this flow regime. A similar problem in measurements of pressure drop in slug flow is reported by Oshinowo [10].

FLOW PATTERN MAP

The pressure drop data collected in the present study was for different flow patterns generated by varying the gas flow rate at constant liquid flow rates. The flow pattern map in terms of phase superficial velocities obtained in the present study for vertical down flow is shown in Figure 3. As can be seen from Figure 3, for low values of liquid superficial velocity and moderate to high gas superficial velocities falling film and annular flow patterns are observed while at moderate to high liquid velocities increase in the gas superficial velocity shifted the flow pattern from bubbly to slug, slug to froth and finally from froth to annular. It is evident from this flow pattern map and the flow pattern pictures that for annular flow regime, as a result of high gas and liquid flow rates, both liquid and gas phase contribute significantly to the frictional pressure drop. Whereas in case of bubbly flow the frictional pressure drop is essentially due to liquid flow (high liquid and low gas flow rate). The variation of frictional pressure drop with varying liquid and gas flow rates associated with individual flow patterns is presented in the next section.

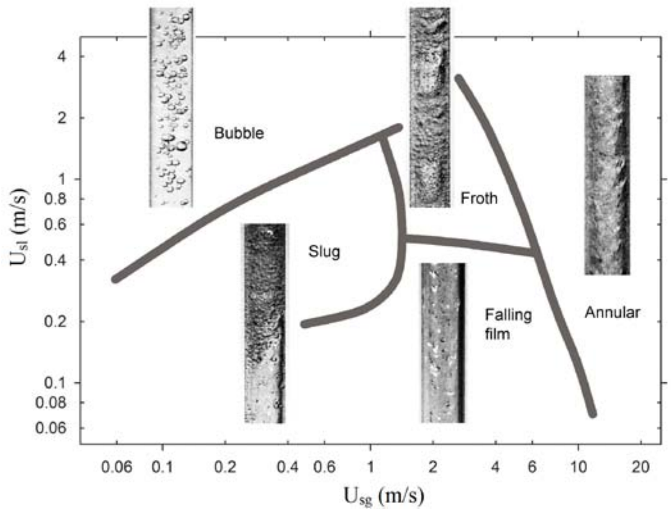

Figure 3 Flow pattern map for vertical downward flow.

HYDROSTATIC PRESSURE DROP

The hydrostatic component of two phase pressure drop is calculated using the two phase mixture density (ρ_m) and hence the void fraction (α). The hydrostatic component is mathematically expressed as shown in Equation (2). It is observed that the calculation of hydrostatic component is very sensitive to the void fraction. As a result a small error in void fraction creates a huge error in prediction of hydrostatic component of pressure drop. Bhagwat and Ghajar [11] evaluated the performance of 26 void fraction correlations and recommended the Gomez et al. [12] correlation as the best correlation to predict void fraction in vertical downward flow. However, in order to achieve better accuracy in higher region of void fraction, Gomez et al. [12] correlation is recommended to be used for a void fraction range of $0 < \alpha < 0.5$, while Woldesemayat and Ghajar [13] correlation should be used for prediction of void fraction in a range of $0.5 < \alpha < 1$. It was also observed in the present study that correlations using two phase density assuming homogeneous flow give highly erroneous results in prediction of hydrostatic component of pressure drop and hence implementation of homogeneous model is never a good choice.

FRICTIONAL PRESSURE DROP

The frictional pressure drop data collected in the present study was measured at constant liquid low rate and varying gas flow rates covering the entire range of void fraction and all flow patterns observed in vertical downward flow. The experimentally measured data was also compared against that of the single phase flow assuming only water flowing through the pipe. This comparison was useful in understanding the influence of interfacial friction and hence the slip between the two phases on frictional component of pressure drop. The slip velocity between the two phases is defined as, $S = U_g - U_l$ where U_g and U_l are the real velocities of the gas and liquid phases. The frictional pressure drop in single phase flow is calculated using Equation (4),

$$\left(\frac{\Delta P}{L}\right)_f = \frac{fG^2}{2D\rho_l} \tag{4}$$

The single phase friction factor (f) is calculated using equation proposed by Churchill [7] and the superficial liquid Reynolds number defined as, $\mathrm{Re}_{sl} = (GD)/\mu_l$. Here, we first present the variation of frictional pressure drop for different flow patterns. This is followed by discussion on influence of pipe diameter and fluid properties on frictional pressure drop. Further, the performance analysis of different pressure drop correlations is presented.

BUBBLY FLOW

The bubbly flow pattern in vertical downward flow is characterized by the flow of gas bubbles through the continuous liquid media distributed around the pipe axis and away from the wall. Thus the frictional pressure drop in bubbly flow is essentially due to the friction of the single phase liquid in contact with the pipe wall in addition to the slippage at gas liquid interface and the turbulence caused by the dispersed bubbles in continuous liquid medium. The experimental data collected in the present study and that reported in literature by Oshinowo [10], Nguyen [14], Beggs [15] and Mukherjee [16] shows that the frictional pressure drop in bubbly flow regime or alternatively the low region of the void fraction is comparable and close to that would occur assuming single phase liquid flow through pipe measured at same mixture mass flow rate. It is seen that the two phase frictional pressure drop approaches the pressure drop that would occur assuming only single phase liquid flowing through the pipe, with increasing superficial liquid Reynolds number (Re_{sl}) and decreasing superficial gas Reynolds number (Re_{sg}) or in other words with decreasing void fraction. To add more insight to the analysis of the frictional pressure drop data, the non-dimensional form of the two phase frictional pressure drop defined as the ratio of two phase frictional pressure drop to its single phase counterpart is plotted against increasing superficial gas Reynolds number as show in Figure 4. It is seen that this ratio as expressed by Equation (5) approaches unity for all constant values of superficial liquid Reynolds number and with decreasing superficial gas Reynolds number. The non-dimensional two phase frictional pressure drop used in the present study is defined as,

$$\phi = \left(\frac{(\Delta P/L)_{f,tp}}{(\Delta P/L)_l}\right) \tag{5}$$

Since there is negligible slip between the two phases for low values of void fraction, the bubbly flow can be approximated as the homogeneous flow and thus the interfacial shear between the two phases can be neglected.

However, this is an approximation and not an accurate formulation. Based on this assumption of homogeneous flow Mukherjee [16] presented a correlation to predict frictional pressure drop in bubbly flow regime. The accuracy of his correlation was not reported. Oshinowo [10] proposed a fluid properties independent correlation for the frictional pressure drop in bubbly flow regime. His correlation predicted the frictional pressure drop data in this regime within +10% and -20% of his own experimentally measured data. In the present investigation it is observed that the two phase frictional pressure drop in bubbly flow increases with increasing both liquid and gas flow rates. For constant liquid flow rates the two phase frictional pressure drop is observed to increase gradually with increasing gas flow rates. A close observation reveals that the increase in frictional pressure drop at low liquid flow rate (Re_{sl} = 18700) is more steep in comparison to that occurs at high liquid flow rates (Re_{sl} = 32800). This trend of variation of two phase frictional pressure drop in bubbly flow regime is illustrated in Figure 4. It is clear that the deviation of the two phase frictional pressure drop from its single phase counterpart increases with increasing superficial gas Reynolds number or alternatively the void fraction. The correlation of Oshinowo [10] was compared against frictional pressure drop data measured in the present study and was found to predict all the data within ±15% error bands. His correlation could not be analyzed against data set of Mukherjee [16] due to scarcity of frictional pressure drop data in bubbly flow regime.

SLUG FLOW

The slug flow pattern is characterized by alternate gas slugs flowing through the pipe creating a hammering effect at pressure taps. The experimental measurement of frictional pressure drop in slug flow regime was little difficult and measurements experienced fluctuating data due to this pulsating nature of slug flow. The frictional pressure drop in slug flow was first observed to increase and then decrease with increasing gas flow rate. As shown in Figure 5 (A)-(B), for gas Reynolds numbers up to 600, the frictional pressure drop increases for all constant superficial liquid Reynolds numbers with the exception of Re_{sl} = 5500, thereafter dips down till Re_{sl} = 1000 and increases again. This anomaly in comparison to other flow patterns is speculated to be a consequence of the balance between the gravity, inertia and buoyancy forces influencing slug flow in vertical downward flow. It was observed by Bhagwat [17] that for vertical downward flow, the slug flow is strongly influenced by the interaction between buoyancy and liquid inertia. For low flow rates of air and water, upward pointing slug was observed, with increasing flow rate of each phase the slug head became flat and finally a downward pointing slug was observed with further increasing phase flow rates.

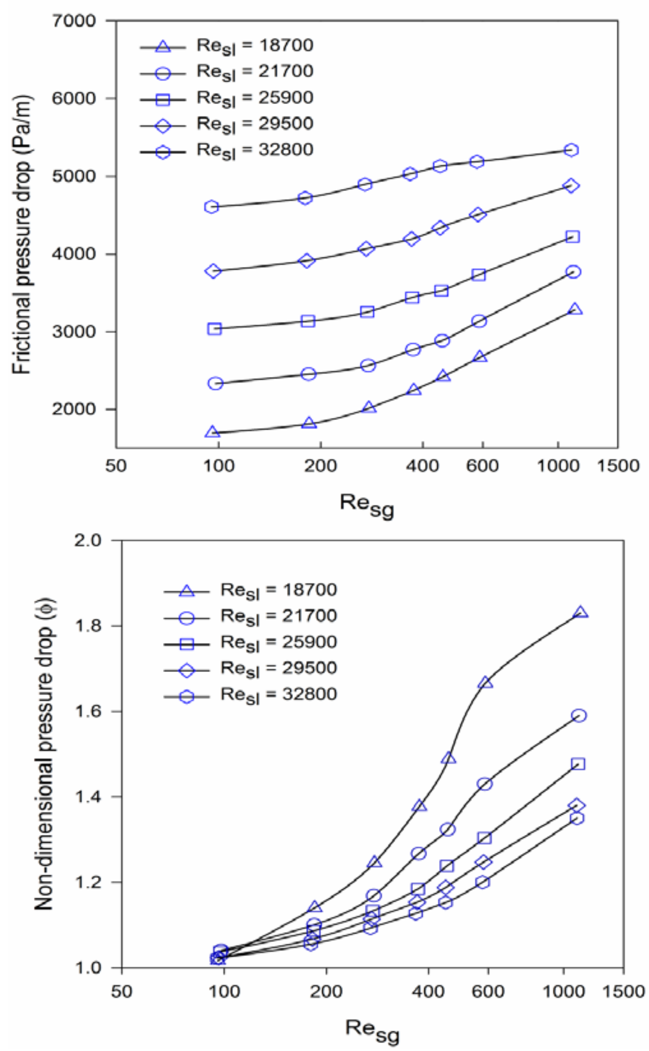

Figure 4 Variation of frictional pressure drop in bubbly flow regime.

The increasing and decreasing trend of the frictional pressure drop observed in the slug flow can be a probable consequence of this phenomenon. However, this trend of the frictional pressure drop data in slug regime could not be verified from other data reported in the literature due to scarcity of pressure drop data in the slug flow regime and hence no confirm comments can be made. Although the frictional pressure drop trend for slug flow is different than other flow patterns, there is a consistency and a systematic shift in the measured pressure drop data at different superficial liquid Reynolds numbers. It is conjectured that the high uncertainty reported earlier in this work is also influenced by this slug flow phenomenon at different flow rates. More experimental work is needed for the frictional pressure drop in slug flow regime.

FROTH FLOW

The froth flow pattern is characterized by rigorous mixing and hence the higher interfacial interaction between the two phases in comparison to bubbly and slug flow and thus the sharp increase in frictional pressure drop is reflected through Figure 6. The overall trend of the frictional pressure drop is observed to increase with increasing superficial gas Reynolds number when measured at constant superficial liquid Reynolds number. The analysis of the non-dimensional form of the pressure drop data revealed continuous increase in the ϕ values as the flow pattern shifted from bubbly to slug, slug to froth and froth to annular flow regime. This indicated the influence and magnitude of the interfacial friction contributing to the total frictional pressure drop in addition to skin friction of liquid phase in contact with the pipe wall.

FALLING FILM FLOW

The falling film flow is characterized by the liquid film gliding smoothly over the pipe surface while gas phase moving through the pipe core. This flow pattern occurs at low liquid flow rates and moderate to high gas flow rates. Thus one can expect the pressure drop due to friction at the pipe wall to be less in comparison to other flow patterns. The present study showed that the frictional pressure drop in falling film region is much larger than that would occur assuming a single phase liquid flow. The interfacial friction is a consequence of the slip between the two phases. Evidently, for a concurrent flow and for Re_{sl} = 1000, the slip between the two phases is greater in comparison to that of Re_{sl} = 5500 thus leading to greater deviation from that of the single phase flow. The interfacial friction is a consequence of the slip between the two phases.

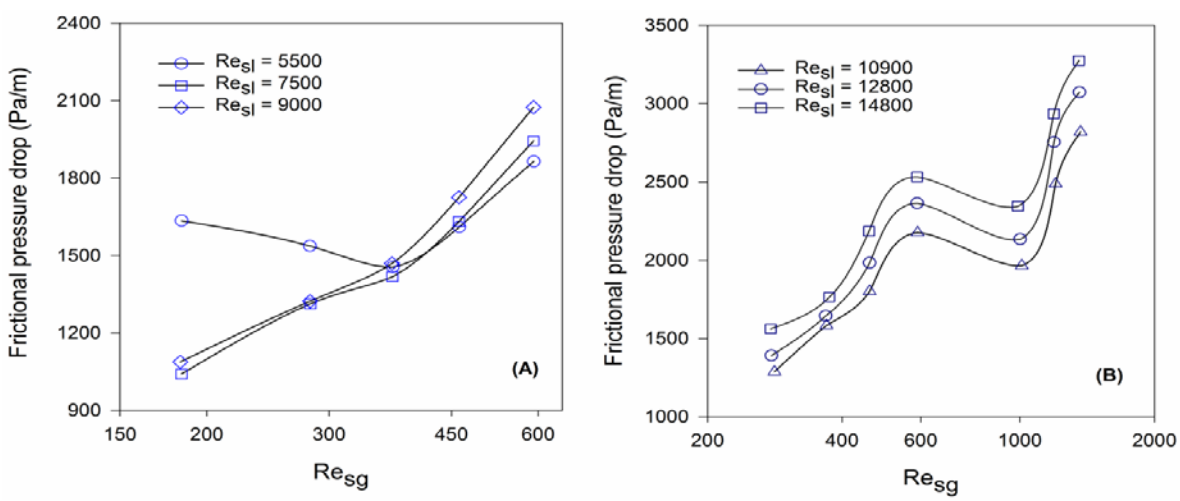

Figure 5 Variation of frictional pressure drop in slug flow regime

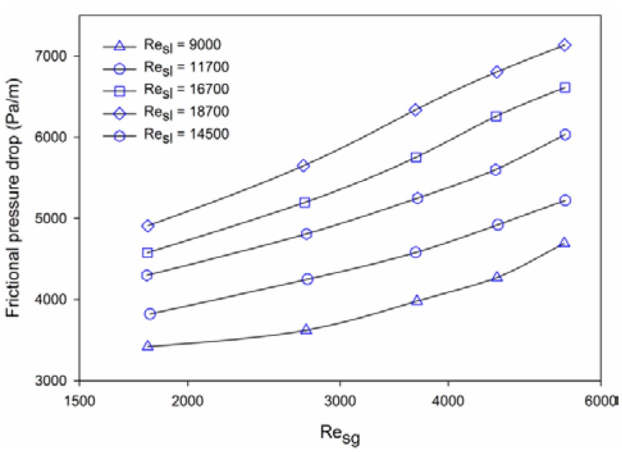

Figure 6 Variation of frictional pressure drop in froth flow regime.

Evidently, for a concurrent flow and for Re_{sl} = 1000, the slip between the two phases is greater in comparison to that of Re_{sl} = 5500 thus leading to greater deviation from that of the single phase flow. It is observed in the falling film flow regime that the frictional pressure drop remained virtually constant with increasing gas flow rate at constant liquid flow rates. However, it was observed to be a function of liquid flow rate i.e. the two phase frictional pressure drop increased with increasing liquid flow rate. Our observations are in agreement with that of Oshinowo [10] and Nguyen [14].

ANNULAR FLOW

The structure of annular flow is similar to that of the falling film flow except the fact that phase flow rates are comparatively high and is qualitatively turbulent in nature. The frictional pressure drop in annular flow is observed to be sensitive to both gas and liquid flow rates. As shown in Figure 7, the frictional pressure drop in annular flow increased sharply with increasing gas flow rate measured at constant liquid flow rate. Although, the range of void fraction encountered in both falling film and annular flow regime is typically $0.75 < \alpha < 1$, the frictional pressure drop observed in both flow patterns is significantly different in nature. It was also observed that the frictional pressure drop in this flow regime deviated significantly from its single phase counterpart and was approximately 30 to 100 fold of that would occur assuming only liquid phase flowing through the pipe. With the aid of data available in the literature it was seen that the frictional pressure drop in annular flow region is significantly influenced by pipe diameter and is discussed next.

EFFECT OF PIPE DIAMETER

The pipe diameter is observed to have significant effect on the magnitude of two phase frictional pressure drop. Due to limited data available in the literature, this effect was analyzed only for bubbly and annular flow patterns for three different pipe diameters including the one used in the present study. It was observed that the frictional pressure drop increased with decreasing pipe diameter. However, the magnitude by which the frictional pressure drop increased with increasing gas flow rate measured at constant liquid flow rate was higher for annular flow in comparison to that in bubbly flow. The data used for this comparison in addition to that collected in the present study is for 0.0254 m and 0.0454 m I.D. pipes using air-water fluid combination available from Oshinowo [10] and Nguyen [14]. Our conclusion is qualitative and is similar to that of Hajiloo et al. [18], who experimentally investigated the effect of pipe diameter on two phase pressure drop in annular flow regime. In bubbly two phase flow or alternatively the low region of the void fraction, the frictional pressure drop was observed to increase gradually with increasing gas flow rate measured at constant liquid flow rate. Due to different pipe diameters, it was difficult to plot this variation of frictional pressure drop at similar superficial liquid Reynolds number or the liquid mass flow rate. However, for Re_{sl} = 35000, the comparison between the present study and that of Oshinowo [10] showed the sensitivity of the pipe diameter to the frictional pressure drop at varying superficial gas Reynolds numbers. As shown in Figure 8 (A).The reduction of pipe diameter by 50% increased the frictional pressure drop by approximately 150%. A similar conclusion can be drawn from the comparison between the data of Oshinowo [10] and Nguyen [14] for Re_{sl} = 54000. In annular flow, the effect of pipe diameter on magnitude of frictional pressure drop was observed to be significant. As can be seen from Figure 8 (B), for D = 0.045 m, the frictional pressure drop increases gradually with increase in gas flow rate and measured at constant liquid flow rate. With decreasing pipe diameter at D = 0.01252 m, a sharp increase is observed in two phase frictional pressure drop. The non-dimensional form of two phase frictional pressure drop was also analyzed for these different pipe diameters in both bubbly and annular flow regimes. It was observed that for larger pipe diameters, the non-dimensional pressure drop is large in comparison to that of the smaller diameter pipe. This means that the deviation of the two phase frictional pressure drop from that of the single phase is greater for larger pipe diameters.

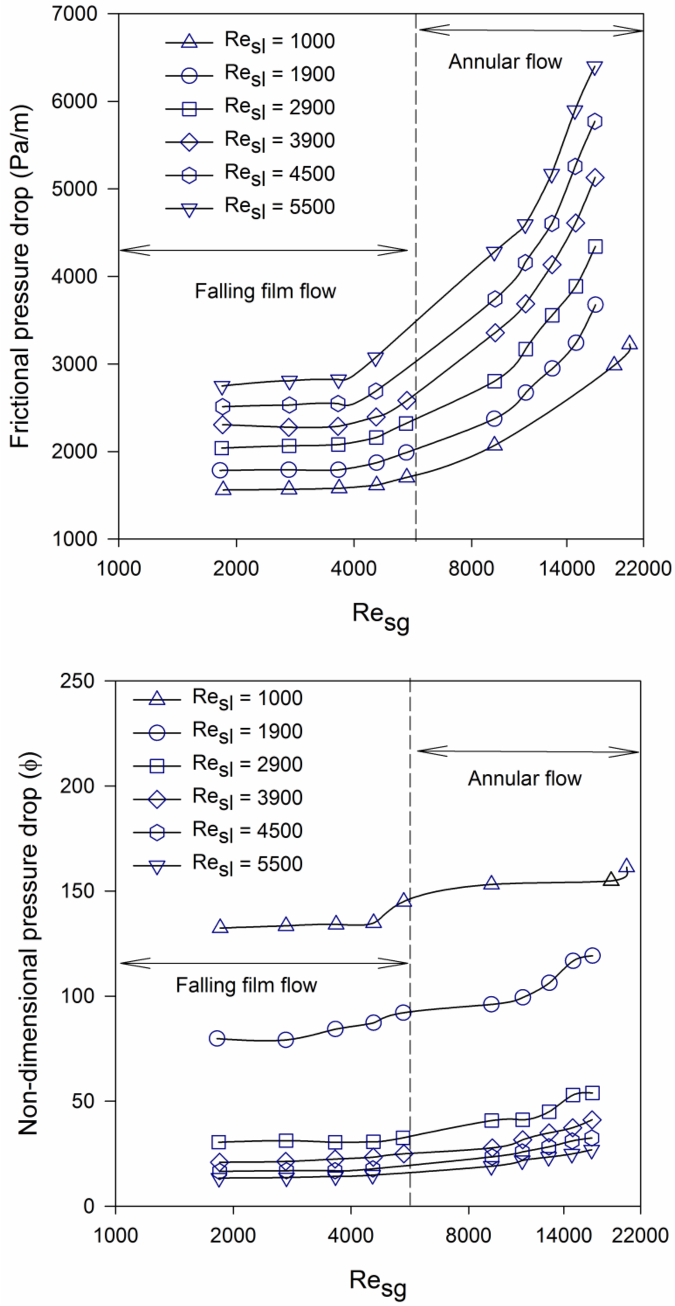

Figure 7 Variation of frictional pressure drop for falling film flow and annular flow.

This is possibly because that for large pipe diameters the surface area available for the interfacial friction is higher in comparison to the smaller diameter pipe resulting in higher non-dimensional two phase frictional pressure drop. This observation for annular flow is similar to that of Hajiloo et al. [18].

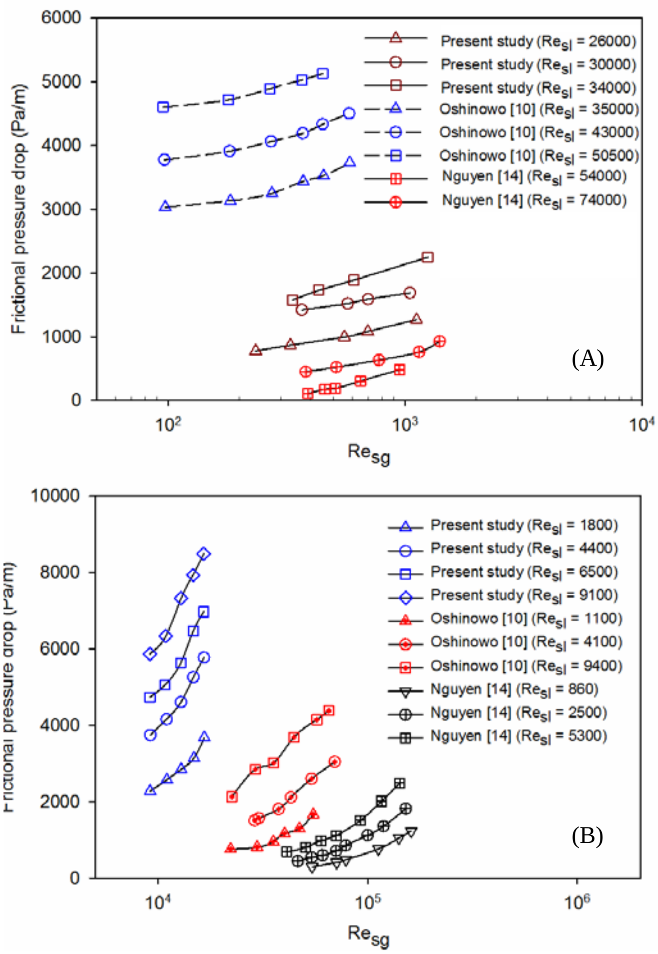

Figure 8 Effect of pipe diameter on frictional pressure drop.

EFFECT OF FLUID PROPERTIES

Effect of fluid properties on the frictional pressure drop is primarily due to the viscosity of the fluid that exerts shearing effect on the pipe wall and at the gas liquid interface. Oshinowo [10] experimentally measured frictional pressure drop for five different fluid combinations including air-water and four different concentrations of glycerin. Based on Oshinowo [10] data, it is clearly observed that the frictional pressure drop increases with increase in fluid viscosity at a fixed gas and liquid flow rate. As shown in Figure 9 (1)-(6), the two phase frictional pressure drop increases significantly with increase in the glycerin concentration, i.e. increase in fluid viscosity. The other probable parameters that can influence the frictional pressure drop are fluid density and surface tension, respectively. Bubbly flow in vertical downward flow is influenced by the interaction between the buoyancy, gravity and inertia forces. In this flow pattern, due to dominant buoyancy effect bubbles try to rise in upward direction, i.e. against the direction of mean flow. Thus it is anticipated that for bubbly flow, both fluid density and dynamic viscosity affect frictional pressure drop. But, as the flow pattern transits to annular flow regime, the buoyancy effect disappears and the fluid dynamic viscosity contributes solely to frictional pressure drop. The correlation proposed by Oshinowo [10] accounts for fluid physical properties but is limited to bubbly flow in its application. The correlation of Fukano and Furukawa [19] was claimed to account for fluid dynamic viscosity in annular flow regime restricted to vertical upward flow. This correlation was analyzed against the annular flow data measured in the present study and that reported by Oshinowo [10] for different fluid combinations. It was observed that the accuracy of this correlation deteriorated with increasing concentration of glycerin.

FRICTIONAL PESSURE DROP CORRELATIONS

The literature reports several correlations to predict frictional pressure drop in two phase flow, but very few of them are developed exclusively for vertical downward flow. The correlations analyzed in the present study include the correlations developed for vertical up, down and horizontal pipe orientations and for both boiling and non-boiling flows. The performance of these correlations is presented in terms of the percentage of data predicted by the correlation within ±10% and ±20% for bubbly flow, ±20% and ±40 % error bands for slug and falling film flows and ±20 % and ±30% for froth and annular flows, respectively. In addition to this the performance of these correlations reported in Table 3 is also presented in terms of mean error and standard deviation. It is found that most of the pressure drop correlations are flow pattern dependent and their accuracy is affected by fluid properties and pipe diameter. All the correlations reported in Table 3 are based on the concept of separated flow model and provide an expression for a two phase friction multiplier or in other words non-dimensional form of two phase frictional pressure drop. As was shown in Figure 4, the magnitude of frictional pressure drop in bubbly flow regime is close to that would occur if assumed that the single phase liquid is flowing through the pipe. This approximates a flow situation with majority of the frictional pressure drop due to friction of single phase liquid at the pipe wall neglecting the friction at gas-liquid interface. Thus the deviation of the two phase pressure drop from its single phase counterpart is less and most of the correlations analyzed in this study were found to be able to predict two phase frictional pressure drop within ±20% of the experimentally measured values. As shown in Table 3, the correlations of Awad and Muzychka [2], Ciccihitti et al. [20], Lau et al. [5], Lockhart and Martinelli [1], Muller-Steinhagen and Heck [21], Shannak [22] and Yamazaki and Yamaguchi [4] predict 100% of the measured data in bubbly flow regime well within ±20% error bands with Muller-Steinhagen and Heck [21] having the least standard deviation of 4.5. The correlation of Fukano and Furukawa [19] totally failed in the bubbly flow regime since this correlation was derived for the annular flow pattern in vertical upward flow.

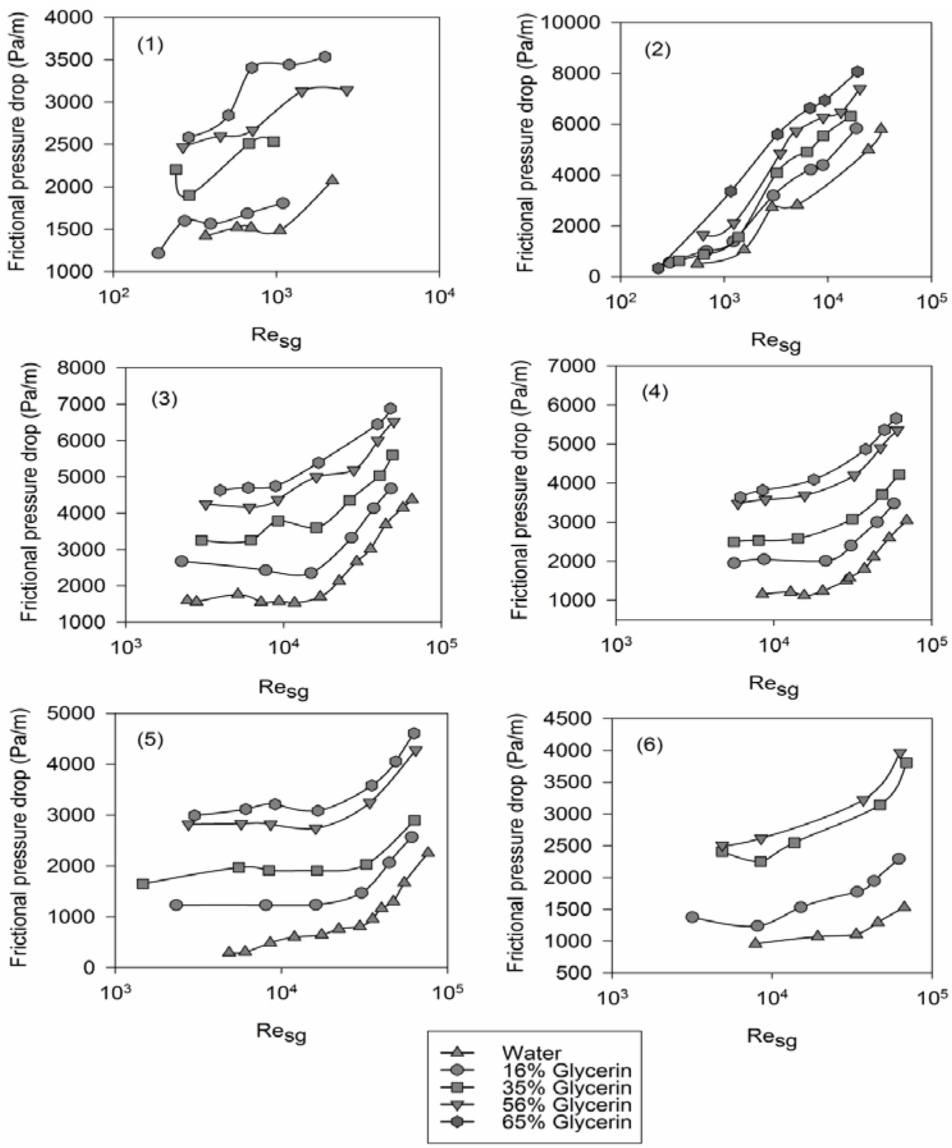

Figure 9 Effect of fluid physical properties on the frictional pressure drop measured at varying gas flow rates and constant liquid mass flow rates as follows: (1) 0.89 kg/s, (2) 0.51 kg/s, (3) 0.15 kg/s, (4) 0.07 kg/s, (5) 0.024 kg/s and (6) 0.008 kg/s.

For the slug flow pattern, none of the correlations analyzed in the present study were able to perform satisfactorily. The criterion for satisfactory performance was the ability of the correlation to predict at least 80% of data within ±40% error bands in slug flow regime. The best performance among these correlations was by Friedel [3] followed by Ciccihitti et al. [20] and Chisholm [23]. Friedel [3] predicted 40.4% and 65.9 % of data within ±20% and ±40% error bands, respectively. It is anticipated that the failure of the correlations in slug flow pattern is due to the anomalous behavior of experimentally measured frictional pressure drop in slug flow regime. The accuracy of the correlations for the froth flow regime was better as compared to the slug flow regime. The correlations of Ciccihitti et al. [20] and Chisholm [23] were observed to predict 89.6% and 86.2 % of the data within ±30% error bands, respectively. The correlation of Yamazaki and Yamaguchi [4] was found to be able to predict the pressure drop data only in the bubbly flow regime since it was derived and was claimed to be good only for $\alpha < 0.3$; a typical region of bubbly flow pattern. In addition to slug flow, the frictional pressure drop in falling film flow was predicted with least accuracy by all the correlations analyzed in the present study. However, the correlation of Chisholm [23] predicted 48.4% and 80.6% of the data within ±20% and ±40% error bands, respectively. The analysis of these correlations showed that particularly for falling film flow, the correlations under predict the frictional pressure drop. This is an indication of inability of the correlations to account for dominant gas-liquid interfacial friction occurring at the low liquid mass flow rates in the falling film flow.

In the annular flow regime, as mentioned earlier the total frictional pressure drop consists of both pressure drop due to friction at the pipe wall and at the gas-liquid interface. The correlations of Fukano and Furukawa [19], Friedel [3], Gronnerud [24], Lau et al. [5] and Yamazaki and Yamaguchi [4] did not perform well and did not predict the two phase frictional pressure drop data within ±30% accuracy. These correlations were found to under predict the frictional pressure drop indicating their inability to account for interfacial friction in annular flow regime. For data collected in the present study for annular flow regime, Ciccihitti et al. [20], Muller-Steinhagen and Heck [21], Lockhart and Martinelli [1] and Shannak [22] correlations predicted more than 95% of the data within ±30% tolerance. The correlation of Fukano and Furukawa [19] developed for vertical upward annular flow regime failed to predict the frictional pressure drop data in vertical downward flow measured in the present study. However, this correlation gave satisfactory results when analyzed against the data of Oshinowo [10] for different fluid combinations. The accuracy of this correlation was observed to deteriorate with increasing concentration of glycerin in water. The top performers in the annular flow regime for the data of present study were Shannak [22] followed by Muller-Steinhagen and Heck [21]. However, when these correlations were compared against the annular flow data of Oshinowo [10] for different concentrations of glycerin, all but Ciccihitti et al. [20] failed to predict frictional pressure drop data. The equations for different correlations analyzed in this study are not reported due to space limitations. Original papers listed in the reference section should be referred for the correlations.

Overall, it was found that the correlations of Ciccihitti et al. [20], Chisholm [23] and Shannak [22] have good potential to predict frictional pressure drop and can be considered for modification and further development to accommodate the effect of pipe diameter and fluid properties. The statistical parameters, i.e. absolute mean error and standard deviation documented in Table 3 are calculated using the following equations:

$$\text{Abs. mean error (\%)} = \frac{1}{N}\sum_{i=1}^{N}\left|\varepsilon_i\right| \tag{6}$$

$$\text{where, } \left|\varepsilon_i\right| = \left|\frac{pred_i - meas_i}{meas_i}\right| \times 100\% \tag{7}$$

$$\text{Std. deviation (\%)}\left(\sigma\right) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\varepsilon_i - \bar{\varepsilon}\right)^2} \tag{8}$$

where N is the number of data points, ε is the error calculated at each data point and the subscripts *meas* and *pred* indicate measured and predicted values of the frictional pressure drop, respectively.

CONCLUSIONS

This study presented new data on air-water two phase frictional pressure drop measured in a 0.01252 m I.D. stainless steel pipe. The presentation of two phase frictional pressure drop data for each flow pattern and its non-dimensional form gave an insight of its magnitude when compared against that would occur in single phase flow. The variation of frictional pressure drop in bubbly flow regime was observed to be close to its single phase counterpart and increased gradually with increasing superficial gas Reynolds number. Most of the correlations available in the literature were found to be able to predict frictional pressure drop in this flow regime. The trend of frictional pressure drop in slug flow regime was observed to be complex in nature with consecutive increase and decrease in its magnitude with increasing superficial gas Reynolds number. This trend could not be compared with other data due to scarcity of slug flow data reported in the literature. The frictional pressure drop in falling film region was observed to stay effectively constant with increasing gas flow rate while a sharp increase in frictional pressure drop was observed as the flow pattern shifted to annular flow regime. This showed the influence of gas flow rate on the frictional pressure drop and resulting different trends in falling film and annular flow regime for a given liquid flow rate. Based on the present experimental data and that of Oshinowo [10] and Nguyen [14], a discussion is presented on the influence of the pipe diameter on two phase frictional pressure drop. It is observed that in comparison to the bubbly flow, frictional pressure drop in annular flow regime is very sensitive to the pipe diameter as a consequence of increase in gas-liquid interfacial friction with increasing pipe diameter. The correlations which proved successful for annular flow regime in the present study, did not perform well for pressure drop data measured in larger pipe diameters by Oshinowo [10] and Nguyen [14]. This indicates the need for a correlation capable to account for larger pipe diameters and hence increase in the interfacial component of frictional pressure drop. The effect of fluid properties on the frictional pressure drop for constant gas and liquid flow rates was also presented in the present study. The quantitative comparison of the present experimental data against several correlations was documented. Majority of the correlations effectively predicted the frictional pressure drop in bubbly flow regime but suffered a loss in accuracy for slug, froth and falling film flow patterns. Conclusively it was observed that the two phase frictional pressure drop is a strong function of flow patterns, pipe diameter and fluid physical properties. The analysis of different correlations in the present study shows their partial ability to predict frictional pressure drop data and hence call for development of a new correlation exercising the influence of aforementioned flow parameters. In addition to this it is also observed that there is a scarcity of frictional pressure drop data in the slug and falling film flow regimes and hence a more detailed experimental study focusing on individual flow patterns is recommended.

Table 3 Performance of frictional pressure drop correlations against the data collected in the present study.

Flow pattern	Parameter	Data Points (Present Study)	Awad and Muzychka [2]	Ciccihitti et al. [20]	Chisholm [23]	Friedel [3]	Fukano and Furukawa [19]	Gronnerud [24]	Lau et al. [5]	Lockhart and Martinelli [1]	Muller-Steinhagen and Heck [21]	Shannak [22]	Yamazaki and Yamaguchi [4]
Bubbly	% data within ±10%	47	51.6	51.6	80.8	0	0	53.2	85.1	72.3	82.9	87.2	30
	% data within ±20%		100	100	97.8	0	0	87.2	100	100	46	100	100
	Abs. mean error		35.8	14.3	17.3	82.1	87.9	44.6	58.3	14.8	14.7	3.23	5.2
	Std. deviation		10.9	7.6	16.9	22	8.9	6.3	12	16.4	4.5	8.07	8.5
Slug	% data within ±20%	47	12.7	17.2	19.1	40.4	0	2.1	6.3	2.1	6.3	10.6	6.3
	% data within ±40%		53.2	53.2	55.3	65.9	0	6.3	46.8	29.8	38.3	51.6	42.6
	Abs. mean error		45.6	44.3	40.3	3.8	99.7	61	47.5	53.8	52	47.1	50.6
	Std. deviation		22.1	22.6	22.6	38.1	0.12	16.3	20.2	17.5	19.1	20.9	20.1
Froth	% data within ±20%	29	20.7	55.2	65.5	0	0	0	3.4	41.4	3.4	27.6	3.4
	% data within ±30%		68.9	89.6	86.2	6.9	0	0	31.3	65.5	13.8	68.9	13.8
	Abs. mean error		28.5	21.4	17.3	37.8	99.1	55.2	37.6	29.3	37	26	44.9
	Std. deviation		8.31	9.07	10.6	11.7	0.49	6.1	9.4	15.8	6.8	8.4	11.2
Falling Film	% data within ±20%	31	0	32.2	48.4	38.7	0	0	0	13.2	3.2	19.3	0
	% data within ±40%		3.2	58.6	80.6	64.5	0	0	0	25.8	32.2	48.4	0
	Abs. mean error		63.6	35.9	17.7	17.1	95	75.9	76.6	62.6	52	42.4	86.1
	Std. deviation		13.4	20.8	13.8	31.8	4.5	10.3	10.7	20.4	15.8	18.5	7.6
Annular	% data within ±20%	53	1.8	75.4	60.3	1.8	39.6	1.8	3.7	84.9	90.5	96.2	0
	% data within ±30%		41.5	98.1	77.3	9.4	67.9	28.3	5.6	95.4	100	100	0
	Abs. mean error		35.8	14.3	17.4	64.7	87.9	44.7	58.4	14.8	14.7	3.2	77.4
	Std. deviation		10.9	7.6	16.9	9.2	9	6.4	12.1	16.4	4.6	8.1	8.6

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