EFFECT OF PIPE SURFACE ROUGHNESS ON FRICTIONAL PRESSURE DROP IN GAS-LIQUID TWO PHASE FLOWS

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ABSTRACT

The main objective of this experimental work is to investigate the effect of pipe surface roughness on frictional component of gas-liquid two phase pressure drop. The pressure drop measurements are carried out with air-water two phase flow in two different flow loops. First flow loop consists of 12.7 mm I.D. (smooth pipe), 12.5 mm (rough pipe) while second flow loop consists of both smooth and rough pipes of 27.8 mm I.D. The smooth and rough pipes are made up of polycarbonate and stainless steel material, respectively. Thus, all experiments are carried out for four different combinations of relative roughness. The gas and liquid flow rates are varied systematically so as to generate all key flow patterns observed in two phase flow. Experimental results show that the increase in the relative roughness increases the frictional pressure drop as a function of both gas and liquid flow rates. This effect is substantial for inertia driven flows (annular flow) compared to bubbly and slug flow patterns. It is also seen that the effect of increase in relative roughness on the frictional pressure drop increases with decrease in the pipe diameter. Moreover, the measurements carried out in 12.7 mm and 12.5 mm I.D. pipes at upward and downward inclinations show that the effect of relative roughness on frictional pressure drop is independent of the pipe inclination. The general trends of frictional pressure drop for different relative roughness are found to be in agreement with the experimental observations reported in literature. Evaluation of the existing two phase flow models developed for smooth pipes show that these correlations under predict the frictional pressure drop in rough pipes.

NOMENCLATURE

D	[m]	Pipe diameter
dp/dz	[Pa/m]	Pressure gradient
G	[kg/m^{2}s]	Mixture mass flux
g	[m/s^2]	Acceleration due to gravity
p_{sys}	[bar]	System pressure
U_{sl}	[m/s]	Superficial liquid velocity
U_{sg}	[m/s]	Superficial gas velocity
x	[-]	Two phase quality

Special characters

α	[-]	Void fraction
ε	[m]	Surface roughness
θ	[deg]	Pipe inclination
ρ	[kg/m^3]	Phase density

Subscripts

a	Accelerational
f	Frictional
g	Gas
h	Hydrostatic
l	Liquid
$meas$	Measured
$pred$	Predicted
r	Rough
s	Smooth
t	Total

INTRODUCTION

Two phase flow investigations carried out in past few decades have been carried out in smooth (copper, polycarbonate, glass) pipes/tubes while little consideration is given to the understanding of thermal hydraulic characteristics of two phase flow in relatively rough pipes. The effect of pipe surface roughness on two phase pressure drop is crucial in applications involving two phase flow through steel or micro-finned tubes. The internally ribbed, corrugated or micro-finned tubes are used in air-conditioning and refrigeration applications to improve the tube side heat transfer, however, at the expense of enhanced pressure drop. There are several studies dedicated to the study of two phase flow in micro-finned tubes and it must be made clear that this study is focused on studying the two phase pressure drop in pipes with microscopic rough surface and not the artificially induced roughness. The practical application of this type of flow would be in case of two phase flow through stainless steel/ metallic tubings with rough microscopic surfaces. Two phase frictional pressure drop is usually determined using the two phase frictional multiplier method (based on separated flow model) or the use of two phase dynamic viscosity models (based on homogeneous flow theory). Both of these methods require use of single friction factor and/or single phase pressure drop. A majority of these correlations based on either method do not take the pipe surface roughness into consideration.

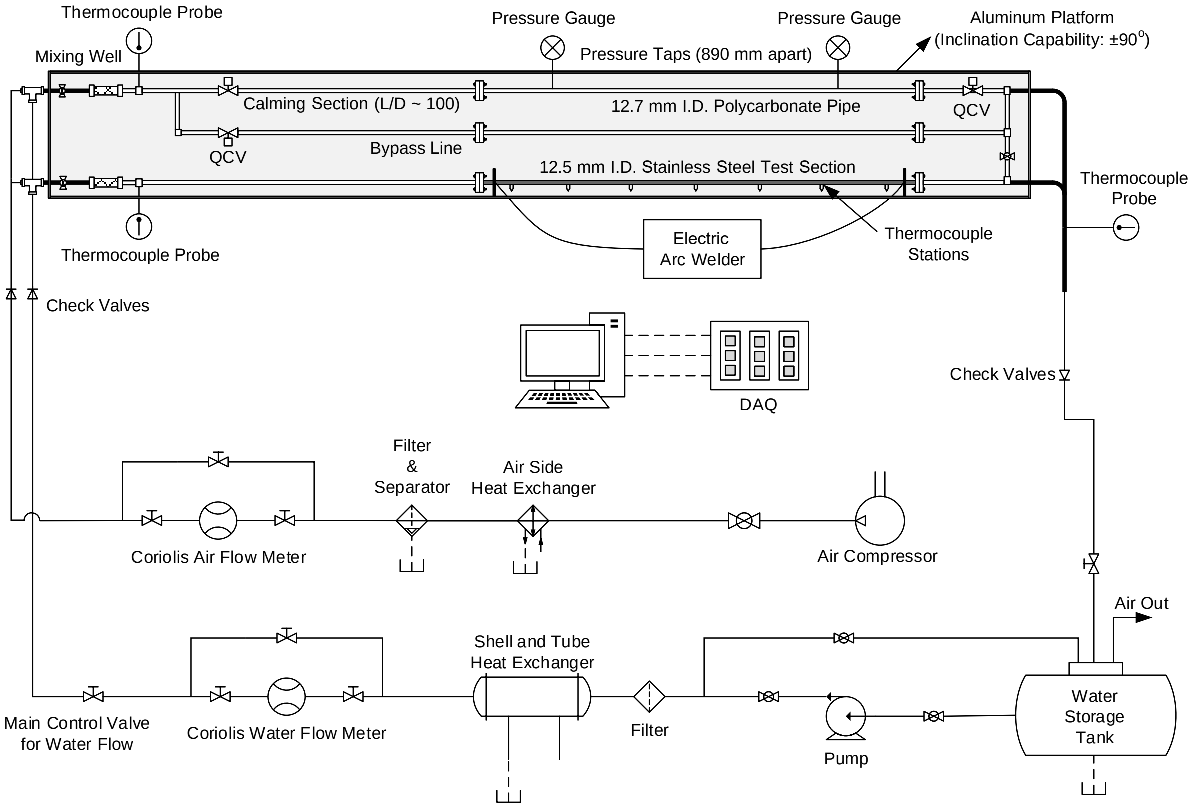

Figure 1. Experimental setup used for flow visualization, void fraction, pressure drop and heat transfer measurements.

Two phase literature reports the work of [1] and [2] (micro-finned tubes), [3] and [4] (micro scale flow), [5] (macro scale flow) that report the effect of surface roughness on two phase pressure drop. Work of [1] is based on the evaporating two phase flow of R134a in smooth and micro-finned tube in 9.5 mm I.D. copper tubing while that of [2] is based on adiabatic two phase flow of R12 in smooth and micro-finned aluminum tube. Their work reported that two phase frictional pressure drop in rough (micro-finned) tube is up to 60% higher than that in smooth pipe. Jones and Garimella [3] and Unni [4] studied the effect of pipe wall surface roughness in micro scale two phase flow in rectangular micro channels. The experimental results of [3] demonstrated that pipe surface roughness may adversely affect the two phase pressure drop and may increase the two phase pressure drop up to 45%. At macro scale, Shannak [5], Chisholm [6] and Bhattacharyya [7] experimented with air-water two phase flow and measured two phase frictional pressure drop in both smooth and rough pipes. Experiments of Shannak [5] were carried out in 52.5 mm I.D. smooth and rough pipes inclined at horizontal and vertical positions. He found that even at macro scale, the pipe relative roughness (ε/D) can enhance the two phase frictional pressure drop by up to 20%. He also noted that this difference between two phase frictional pressure drop in smooth and rough pipes depends upon the two phase mixture mass flux and the two phase quality to a great extent. Based on his measurements, he also proposed a two phase friction factor model (a modified form of single phase friction factor correlation of Chen [8] based on two phase mixture Reynolds number) to account for the effect of relative roughness on two phase frictional pressure drop. On a similar note, this study attempts to experimentally study the effect of pipe surface roughness on two phase frictional pressure drop of air-water two phase flow. The two phase frictional pressure drop is measured in a 12.7 mm I.D. transparent polycarbonate (smooth) and a 12.5 mm I.D. stainless steel (rough) pipe. These two pipe surfaces yield relative roughnesses of $\varepsilon/D = 0.0001$ and $\varepsilon/D = 0.0016$ for smooth and rough pipes, respectively. Based on these measurements, a distinct difference in measured values of two phase frictional pressure drop is observed. Additionally, the combined effect of pipe inclination and ε/D on the two phase frictional pressure drop is also studied. Finally, based on these measurements, the performance of existing two phase pressure drop correlations is analyzed.

EXPERIMENTAL SETUP

The experimental setup shown in Figure 1 is used for two phase frictional pressure drop measurements. The experimental setup consists of a 12.7 mm I.D. polycarbonate pipe ($\varepsilon/D = 0.0001$) and a 12.5 mm I.D. schedule 40S stainless steel pipe ($\varepsilon/D = 0.0016$) test sections mounted on a variable inclination frame. The air supplied by Ingersoll Rand T-30 Model 2545 compressor first passes through a regulator, filter and lubricator circuit and then through a submerged helical coil heat exchanger.

Next, the air is again passed through a filter and then fetched to Micro Motion Elite Series Model LMF 3M and CMF 025 Coriolis gas mass flow meters where the mass flow rate of air is controlled precisely using a Parker (24NS 82(A)-8LN-SS) needle valve. The compressed air is then allowed to enter the test section through a spiral static mixer. The liquid phase in form of distilled water stored in a 50 gallon tank is circulated in the system using a Bell and Gosset (series 1535, model number 3445 D10) centrifugal pump. The distilled water is first passed through Aqua-pure AP12-T purifier and then through ITT model BCF 4063 shell and tube heat exchanger. The distilled water is then passed through an Emerson Coriolis mass flow meter (Micro Motion Elite Series model number CMF 100) where the mass flow rate of the liquid phase entering the test section is controlled. Later, the water is allowed to mix with air in Koflo model 3/8-40C-4-3V-23/8 static mixer. The mixer is mounted right before the entrance to the test section. Two phase flow measurements are carried out for all major flow patterns by systematically varying the gas flow rates for fixed value of liquid flow rates. During all measurements, the system temperature is maintained between 20 to 25 °C and the system pressure is found to vary between 1 to 3 bar. For each combination of gas and liquid flow rate, void fraction (α) is measured using quick closing valves. The total two phase pressure drop ($(dp/dz)_t$) across pressure taps placed 890 mm apart is measured using a DP15 variable reluctance Validyne pressure transducer having an accuracy of 0.25% of full scale range of the diaphragm. The two pressure diaphragms with an upper limit of 3.5 kPa and 14 kPa are used to measure total two phase pressure drop. From the measured total two phase pressure drop, frictional component ($(dp/dz)_f$) is calculated by subtracting hydrostatic component ($(dp/dz)_h$) as given by equation (1) to equation (3). Hydrostatic component of pressure drop is a function of void fraction, gas and liquid phase density (ρ_l and ρ_g) and the pipe inclination (θ). Note that accelerational pressure drop ($(dp/dz)_a$) is negligible for non-boiling flows and hence can be ignored.

$$\left(\frac{dp}{dz}\right)_t = \left(\frac{dp}{dz}\right)_h + \left(\frac{dp}{dz}\right)_f + \left(\frac{dp}{dz}\right)_a \tag{1}$$

$$\left(\frac{dp}{dz}\right)_h = [\rho_l(1-\alpha)+\rho_g\alpha]\, g\sin\theta \tag{2}$$

$$\left(\frac{dp}{dz}\right)_f = \left(\frac{dp}{dz}\right)_t - \left(\frac{dp}{dz}\right)_h \tag{3}$$

The other experimental setup (flow loop) used in this work consists of 27.8 mm I.D. pipes made of transparent polycarbonate material and stainless steel with a relative roughness (ε/D) of 0.00005 and 0.00072, respectively. Relative roughness for each pipe is determined using the surface roughness data provided by the pipe manufacturer. Note that these two flow loops (experimental setups) are operated one at a time and are constructed in such as way that they share water and air source, pump, mass flow meters and instrumentation system. This second flow loop is used for pressure drop measurements in horizontal inclination only at selected flow rates ($G = 300\,\mathrm{kg/m^2s}$ and $600\,\mathrm{kg/m^2s}$). The accuracy of these measurements is verified by comparing the measured values of single phase friction factor against those obtained from Churchill [9] correlations. The experimental uncertainty associated with frictional pressure drop is determined using Kline and McClintock [10] method. Note that experimental uncertainty in measurement of $(dp/dz)_f$ depends on the pipe inclination and void fraction yielding the uncertainty in a range of ±35 to ±120 Pa/m as the pipe is inclined from horizontal to vertical.

RESULTS AND DISCUSSION

The experimental data for two phase frictional pressure drop measured in smooth ($\varepsilon/D = 0.0001$) and rough ($\varepsilon/D = 0.0016$) pipes for 12.7 mm and 12.5 mm I.D. flow loop is presented in this section. As mentioned earlier, for each value of two phase mixture mass flux, gas and liquid flow rates are varied systematically to ensure the two phase flow conditions encompass all key flow patterns reported in two phase flow literature. The associated flow patterns for different ranges of superficial gas and liquid velocities are also identified in the presentation of the measured data. The experimental data (frictional pressure drop in smooth and rough pipes) measured in 12.7 mm (smooth) and 12.5 mm (rough) I.D. pipe is presented in Figure 2 to Figure 5 for four different two phase mixture mass fluxes (G) of $160\,\mathrm{kg/m^2s}$, $310\,\mathrm{kg/m^2s}$, $460\,\mathrm{kg/m^2s}$, and $610\,\mathrm{kg/m^2s}$, respectively.

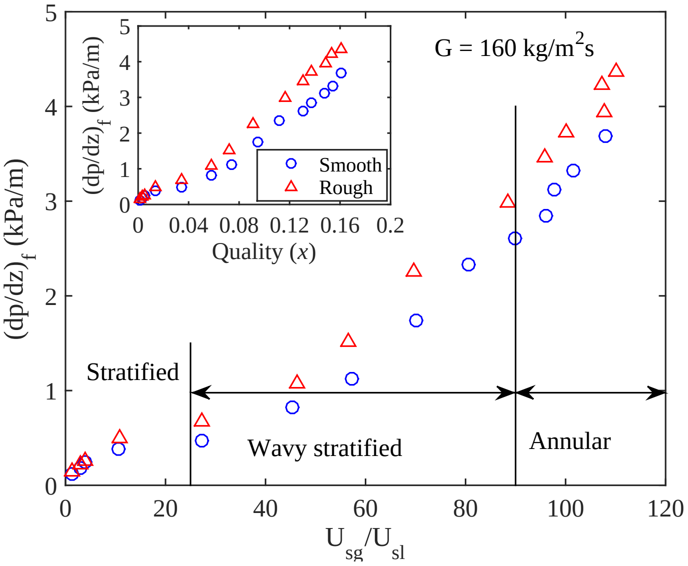

Figure 2. Effect of pipe surface roughness on two phase frictional pressure drop at $G = 160\,\mathrm{kg/m^2s}$ (smooth pipe: $\varepsilon/D = 0.0001$, rough pipe: $\varepsilon/D = 0.0016$).

Additionally, the variation of this data is also presented with variation of the two phase quality (x). It is evident that the effect of pipe surface roughness or alternatively the relative roughness (ε/D) is significant at higher values of superficial gas to liquid velocity ratios (U_{sg}/U_{sl}) that represent inertia driven regime

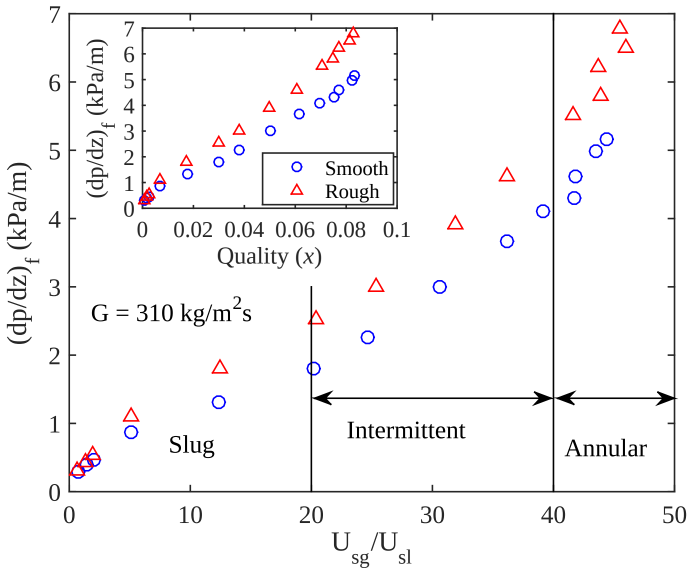

Figure 3. Effect of pipe surface roughness on two phase frictional pressure drop at $G = 310\,\mathrm{kg/m^2s}$ (smooth pipe: $\varepsilon/D = 0.0001$, rough pipe: $\varepsilon/D = 0.0016$).

of the two phase flow. The effect of relative roughness on two phase frictional pressure drop is also observed to increase with the increase in two phase mixture mass flux. In the inertia driven regime of the two phase flow i.e., wavy annular (part of intermittent flow) and annular flow pattern, the effect of increase in (ε/D) is to increase the two phase frictional pressure drop by up to 40% depending upon the gas and liquid flow rates. Even at low mixture mass flux ($160\,\mathrm{kg/m^2s}$), two phase frictional pressure drop in rough pipes is up to 25% higher than that measured in smooth pipes. Note that the inertia driven region and the corresponding U_{sg}/U_{sl} ratio is associated with wavy and annular flow regimes visually observed in this experimental work.

For any given mass flux, the effect of relative roughness on frictional pressure drop at lower gas to liquid velocity ratios ($U_{sg}/U_{sl} \lesssim 5$) or lower two phase flow qualities is found to be negligible and hence can be ignored. This is essentially because at these flow rates, the flow pattern is bubbly or slug in nature such that the partial circumference of pipe is in contact with the gas phase moving at low velocity and hence offers little wall drag compared to the case of inertia driven region where the entire pipe circumference is wetted by liquid film. In terms of the percentage difference, this effect may be up to 10% however, the difference in absolute values of $(dp/dz)_f$ is insignificant. These observations are in agreement with the findings of Shannak [5] who experimented with air-water and measured two phase frictional pressure drop in smooth and rough pipes of diameter 52.5 mm inclined in horizontal and vertical directions. Figure 6 (a) and (b) reports his findings that a prominent effect of relative roughness on two phase frictional pressure drop is observed for higher values of two phase mass flux and qualities ($x > 0.5$). The maximum increase in frictional pressure drop due to the surface roughness was reported to be 20% at $G = 700\,\mathrm{kg/m^2s}$ and $x = 0.8$. Note that qualitatively, this trend is similar to the one observed in this work. However, the range of two phase flow quality and the velocity ratio (U_{sg}/U_{sl}) at which a significant effect of relative roughness on two phase pressure drop is observed is quite different. This is essentially because of the difference in the gas phase density (due to difference in system pressure) associated with the present study ($\rho_g \approx 1.25 - 3\ \mathrm{kg/m^3}$) and that of Shannak [5] ($\rho_g \approx 16.5\,\mathrm{kg/m^3}$). Interestingly, there is a good agreement between these two studies in terms of the presence of the relative roughness effect on frictional pressure drop during annular flow (inertia driven region). The existence of annular

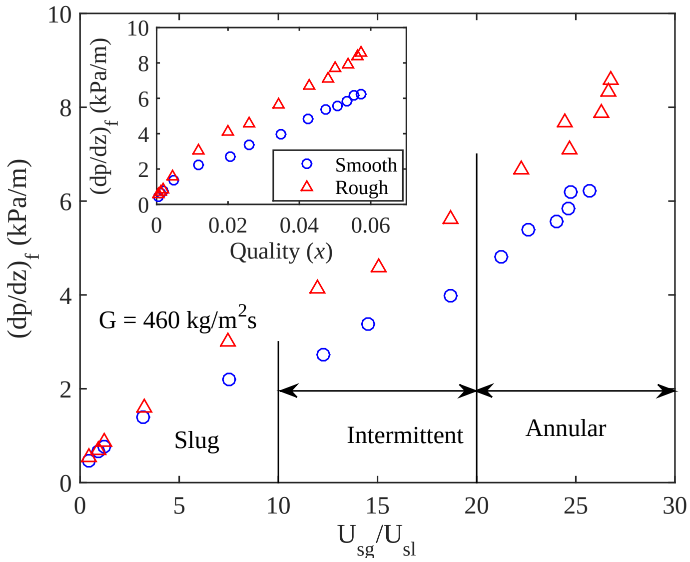

Figure 4. Effect of pipe surface roughness on two phase frictional pressure drop at $G = 460\,\mathrm{kg/m^2s}$ (smooth pipe: $\varepsilon/D = 0.0001$, rough pipe: $\varepsilon/D = 0.0016$).

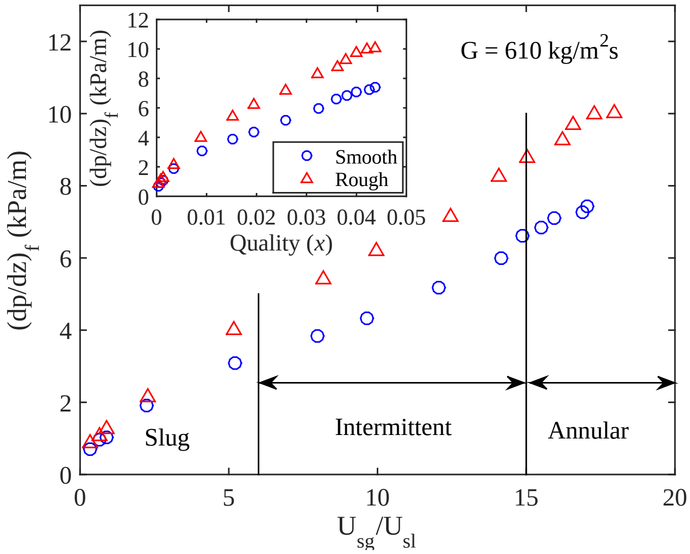

Figure 5. Effect of pipe surface roughness on two phase frictional pressure drop at $G = 610\,\mathrm{kg/m^2s}$ (smooth pipe: $\varepsilon/D = 0.0001$, rough pipe: $\varepsilon/D = 0.0016$).

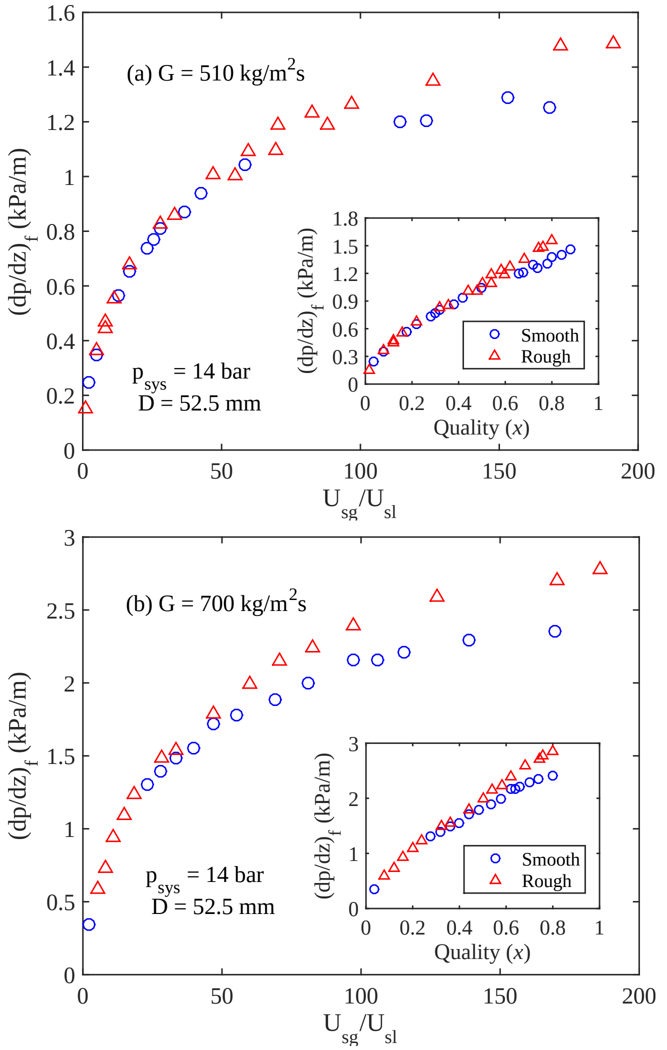

Figure 6. Effect of pipe surface roughness on two phase frictional pressure drop (data of [5], smooth pipe: $\varepsilon/D = 0.00001$, rough pipe: $\varepsilon/D = 0.0001$)

flow pattern in these studies could be confirmed by analyzing void fraction (α) against two phase flow quality (x). Two phase literature and recent work of Cioncolini an Thome [11] shows that annular flow prevails for void fraction approximately greater than 0.75. Thus, even if two phase quality is significantly different from that of [5], the effect of relative roughness on two phase frictional pressure drop is experienced for large values of void fraction ($\alpha > 0.75$) that corresponds to wavy-annular and annular flow patterns. With reference to Figure 7, the quality corresponding to existence of annular flow for present study and that of [5] is around 0.04 and 0.5, respectively. A close look at Figures 2 and 6 show a significant difference between frictional pressure drops measured in smooth and rough pipes at these qualities. Thus, it can be said that regardless of the two phase flow quality and fluid properties, the effect of surface roughness on two phase frictional pressure drop is prominent as the two phase flow becomes inertia driven in nature or alternatively the region of two phase flow associated with high values of void fraction.

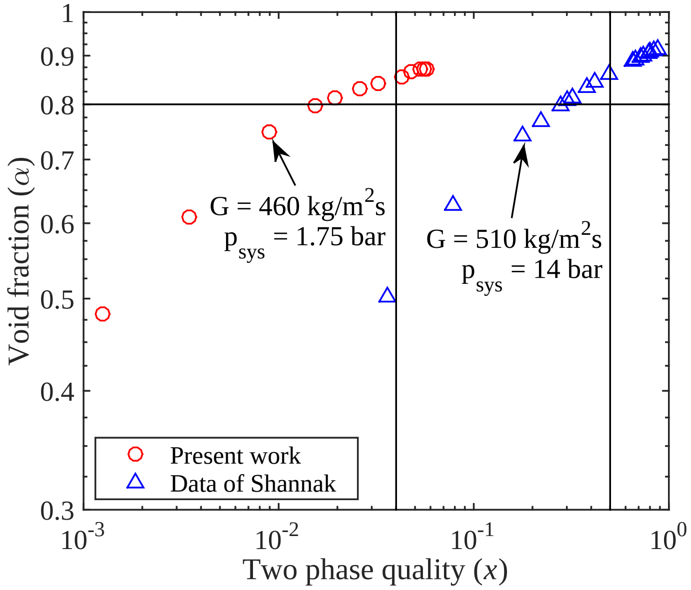

Figure 7. Void fraction versus two phase flow quality at near atmospheric (present work) and relatively higher system pressures data of [5].

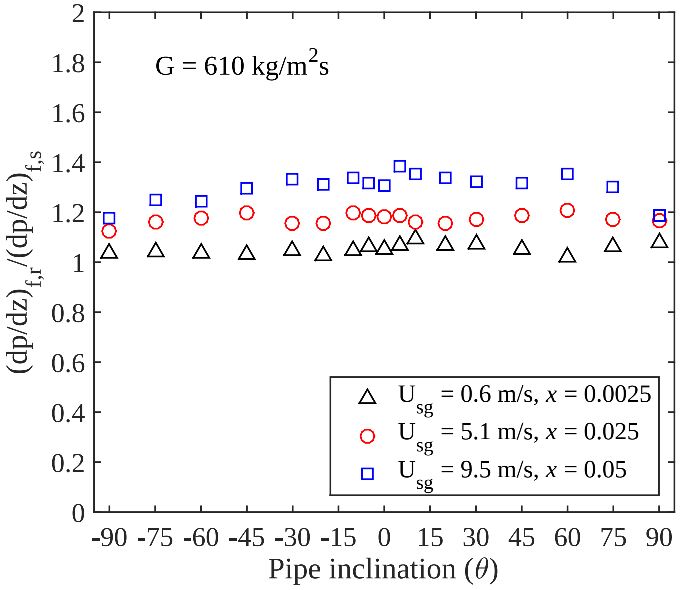

Figure 8. Variation of the ratio of two phase frictional pressure drop in rough pipe to that of smooth pipe with change in pipe inclination.

As mentioned earlier, the experimental setup used in this work could be inclined to any inclination with reference to horizontal and hence for selected flow rates, the frictional pressure drop in rough pipes is also measured at several different pipe inclinations measured from horizontal. For a fixed value of two phase mixture mass flux ($G = 610\,\text{kg/m}^2\text{s}$) and three different superficial gas velocities (or alternatively two phase flow qualities), the ratio of frictional pressure drop measured in rough pipe to that of smooth pipe is presented in Figure 8 for different upward and downward pipe inclinations. It appears that the ratio $(dp/dz)_{f,s}/(dp/dz)_{f,r}$ is fairly uniform for the entire range of pipe inclinations at both low and high values of gas flow rates. In Figure 8, flow patterns corresponding to low, moderate and high gas flow rates are slug, intermittent and wavy annular, respectively. Thus, it can be concluded that the effect of pipe surface roughness on two phase frictional pressure drop is more or less similar at all pipe inclinations. Thus, any form of correlation that can account for this ε/D effect on $(dp/dz)_f$ at horizontal pipe inclination can also possibly work for other inclinations provided the flow pattern remains unchanged.

It must be cautioned that this conclusion may not be extrapolated to the low mixture mass fluxes in downward pipe inclinations since at these inclinations, stratified flow pattern is dominant and it is significantly different in flow structure and behavior compared to other flow patterns in upward pipe inclinations.

ASSESSMENT OF TWO PHASE PRESSURE DROP CORRELATIONS

One of the objectives of this study is also to check the ability of different two phase pressure drop correlations available in literature to correctly predict the two phase pressure drop in smooth and rough pipes. The correlations considered in this work are those of Shannak [5], Chisholm [6], Lockhart and Martinelli [12], Kim and Mudawar [13], Muller-Steinhagen and Heck [14] and Mishima and Hibiki [15]. Note that except for the correlation of [5], all other correlations use single phase friction factor (in the calculation of two phase frictional multiplier) correlation developed for smooth pipe. Readers are suggested to refer to the original papers to get more details about these two phase pressure drop correlations. The performance of these correlations against the data collected in this work as well as that of [5] is reported in Table 1. For smaller diameter pipe (12.7 mm and 12.5 mm I.D. pipe), Mishima and Hibiki [15] predicts the two phase frictional pressure drop in smooth pipe with highest accuracy while the correlation of Kim and Mudawar [13] exhibits overall highest accuracy for both smooth and rough pipes. It is interesting to note that both of these correlations are developed for two phase flow through mini channels and yet predict the data correctly for flow through a relatively bigger diameter pipe. Except for Kim and Mudawar [13] and Shannak [5], all correlations suffer a loss in accuracy when analyzed against the data measured in rough pipes. This is obviously because these correlations are developed based on data for smooth pipes and have no inherent physical variable to account for the effect of surface roughness on two phase frictional pressure drop. It appears that although the correlation of Kim and Mudawar [13] is based on the pressure drop data in smooth pipes, it tends to over predict the data in smooth pipe and hence predicts the data in rough pipe with better accuracy. This trend of [13] for the data measured in the present study is evident from Figure 9. The outliers are found to belong to the data of [5] measured in 52.5 mm I.D. pipe.

For the two phase frictional pressure drop data collected in 27.8 mm I.D. smooth and rough pipes, [5], [13] and [15] are the top three performing correlations that predict more than 75% and 90% of data points within ±20% and ±30% error bands, respectively. With the exceptions of [13] and [5], the accuracy of all other correlations tend to deteriorate with increase in the relative roughness. Finally, for the data of [5], his own correlation predicts more than 90% of data within ±20% and ±30% error bands for both smooth and rough pipes. Whereas, all other correlations exhibit a poor performance in correct prediction of the two phase frictional pressure drop. This is possibly because of the fact some of these correlations for instance [15] and [13] correlations are developed for mini and micro scale two phase flow

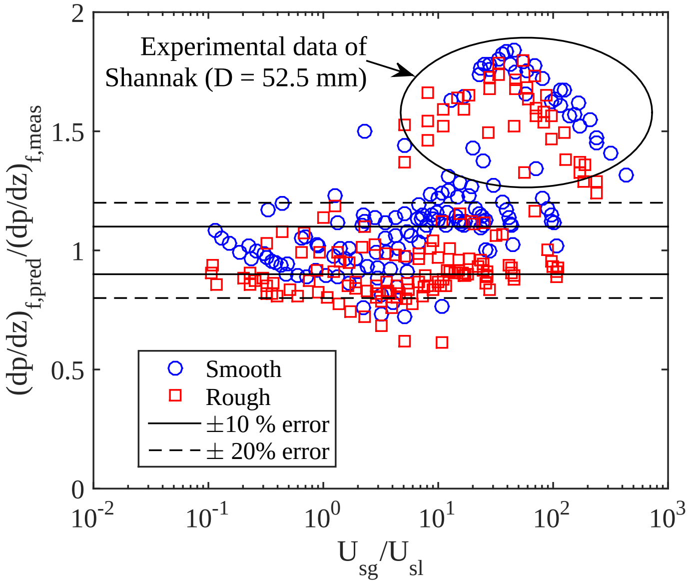

Figure 9. Prediction of Kim and Mudawar [13] correlation against the frictional pressure drop data in smooth and rough pipes.

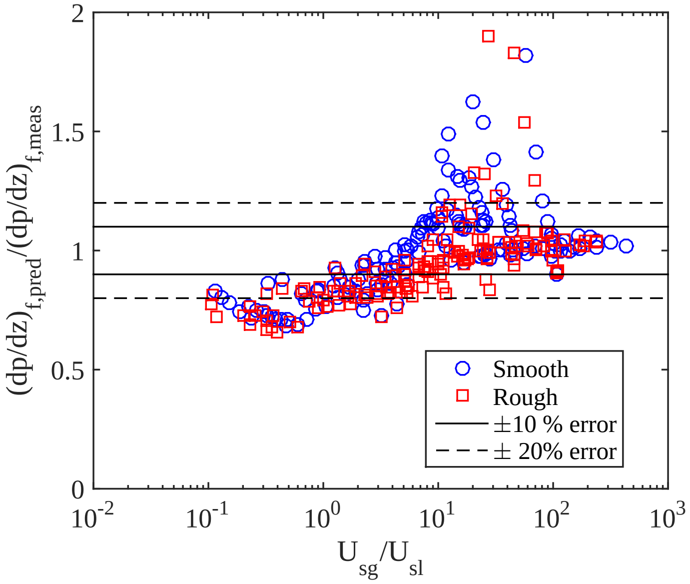

Figure 10. Prediction of Shannak [5] correlation against the frictional pressure drop data in smooth and rough pipes.

Table 1. Performance analysis of different two phase frictional pressure drop correlations for smooth and rough pipes.

Correlation	Present study (D = 12.7/12.5 mm)				Present study (D = 27.8 mm)				Shannak [5] (D = 52.5 mm)			
	Smooth† (93)		Rough (93)		Smooth (24)		Rough (24)		Smooth (33)		Rough (36)	
Relative roughness	$\varepsilon/D = 0.0001$		$\varepsilon/D = 0.0016$		$\varepsilon/D = 0.00005$		$\varepsilon/D = 0.00072$		$\varepsilon/D = 0.00001$		$\varepsilon/D = 0.0001$	
Error bands	±20%	±30%	±20%	±30%	±20%	±30%	±20%	±30%	±20%	±30%	±20%	±30%
Shannak [5]	64.6	84.9	72.1	88.2	79.2	100	91.6	97.8	93.9	96.9	94.4	100
Chisholm [6]	47.3	76.3	36.5	68.8	67.5	91.6	66.6	100	9.9	24.4	16.6	27.7
Lockhart and Martinelli [12]	66.6	75.6	49.4	70.9	79.1	87.5	62.5	81.3	0	3	2.7	8.3
Kim and Mudawar [13]	80.6	92.5	87.1	93.5	75.2	92.3	93.5	100	6.6	12.2	13.8	25
Muller - Heck [14]	43.1	80.6	33.7	45.1	66.7	87.5	28.1	70.8	51.5	75.7	69.5	94.4
Mishima and Hibiki [15]	83.9	93.5	73.1	97.8	87.5	96.5	79.6	91.6	0	3.3	0	2.8

† Numbers next to pipe surface texture smooth and rough indicate number of data points for each case.

and hence cannot correctly predict the frictional pressure drop in 52.5 mm I.D. pipe. The prediction of Shannak [5] correlation against the entire data reported in Table 1 is shown in Figure 10. It is evident that [5] correctly accounts for the effect of ε/D on two phase frictional pressure drop and hence predicts the data correctly in inertia driven region (high values of U_{sg}/U_{sl}).

CONCLUSIONS

This study presents new data on frictional pressure drop of air-water two phase flow in both smooth and rough pipes. Experiments carried out in transparent polycarbonate (smooth) pipe and stainless steel (rough) pipe show that increase in relative roughness affects the two phase frictional pressure drop considerably in inertia driven nature (part of intermittent and annular) two phase flow. The increase in frictional pressure drop due to increase in surface roughness depends upon gas and liquid flow rates as well as pipe diameter. Comparatively, this relationship is found to be insensitive to the change in pipe inclination. Performance analysis of some of the widely used correlations reveal that they do not correctly account for the effect of ε/D on frictional pressure drop. Overall, the correlation of Kim and Mudawar [13] gives good prediction and may be modified to consider the effect of surface roughness on frictional pressure drop in small diameter pipes. Correlation of [5] may be used to model the two phase frictional pressure drop in both smooth as well as rough pipes of relatively larger diameter.

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