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TWO-PHASE FRICTIONAL PRESSURE LOSS IN HORIZONTAL BUBBLY FLOW WITH 90-DEGREE BEND

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ABSTRACT

The two-phase pressure drop due to the minor loss in horizontal bubbly two-phase flow is studied. In particular, geometric effects of a 90-degree elbow is of interest in the present study. Experiments are performed in air-water two-phase flow near atmospheric pressure condition in round glass tube with inner diameter of 50.3mm. Along the test section, 90-degee elbow is installed at L/D=206.6 from the two-phase mixture inlet. Experiments are performed in 15 different flow conditions and the local static pressures are measured at five axial locations. Characteristic pressure drop due to the elbow is clearly demonstrated in the profiles of local pressure data along the axial direction. It is also found that the elbow effect propagates and is more significant further downstream than immediate downstream of the elbow. The overall two-phase frictional pressure loss between L/D=0 and 329 can be predicted well with the Lockhart-Martinelli correlation with parameter C=25, which is higher than the generally accepted value of C=20. A correlation for the two-phase pressure loss, including the minor loss due to the 90-degree elbow is developed by employing the approach analogous to that of Lockhart-Martinelli's. The newly developed correlation suggests that the modified parameter, *C*=65 fits best with the experimental data. In addition, the two-phase minor loss factor for the 90-degree elbow is found to be *k*=0.58, 50% higher than that recommended for single-phase flow.

INTRODUCTION

Two-phase pressure loss is one of the most fundamental design parameters closely related to the performance of a two-phase flow system. Because of this, there have been a number of studies related to pressure drop in various two-phase flow configurations[1-5]. In many practical engineering systems, two-phase flow is transported through horizontal channels interconnected via various flow restrictions, through which significant changes in pressure occur as well as interfacial structure and regime transition. Considering that the horizontal flow configurations are frequently encountered in both traditional light water reactor systems and advanced reactor systems, such as APWR, ABWR and ACR-700, lack of experimental database and accurate models present a serious shortcoming in thermal-hydraulic reactor system analysis. In view of this, present study performs experimental study to develop a predictive model for two-phase frictional pressure loss that accounts for minor loss due to a 90-degree elbow in horizontal bubbly two-phase flow conditions.

EXPERIMENTAL FACILITY

A simplified schematic diagram of the horizontal two-phase test facility employed in the present study is shown in Fig. 1. The test section is made with round Pyrex tubes with inner diameter of 50.3 mm. Along the test section, a 90-degee Elbow is installed at L/D=206.6 from the two-phase mixing chamber (P0). The 90-degree elbow employed in the present study has a radius of curvature of 76.2 mm with an $(L/D)_{elbow}$ of approximately 6. Detailed dimension of the elbow is shown in the inset of Fig. 1. Along the test section, five pressure taps are installed as denoted in the figure as P0 through P4. The local pressure tap located right after the two-phase mixing chamber is chosen as a reference point and denoted as P0 (or L/D=0). Hence, the port P1 is located at L/D=197 from P0 (or 9.5 L/D's before the 90-degree Elbow), and the ports P2, P3 and P4 are located at L/D=225, 250 and 329 from P0 (or 18.1, 43.9 and 122.7 L/D's downstream of the elbow), respectively.

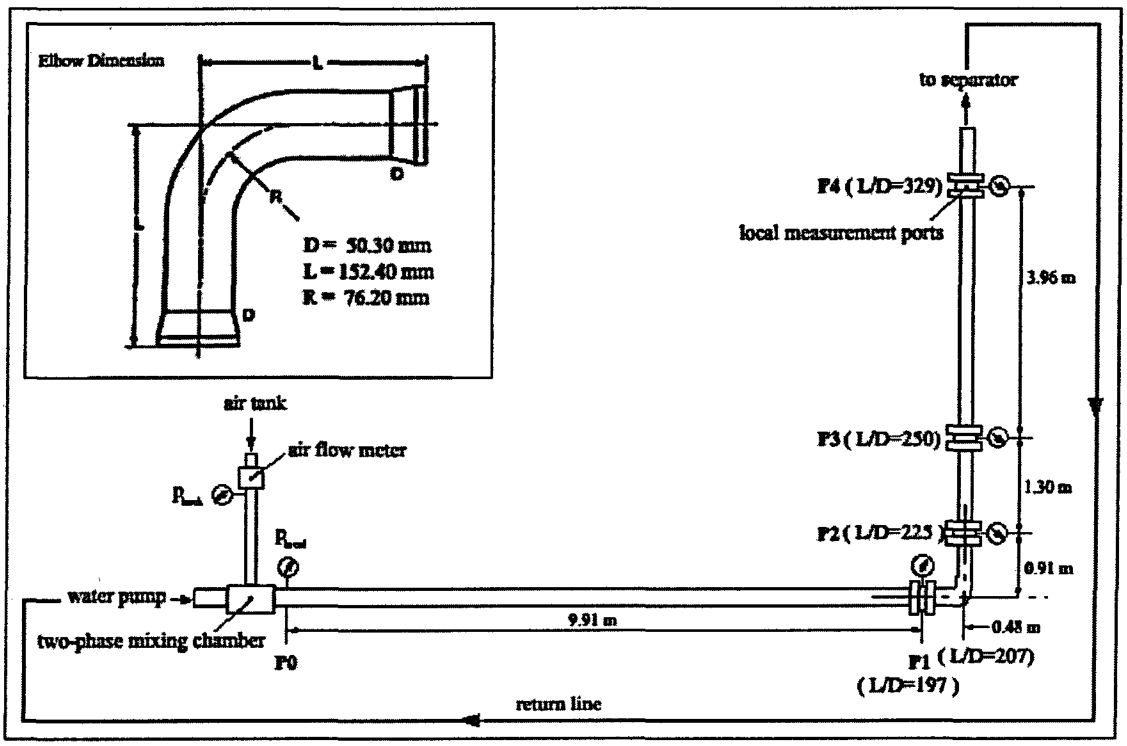


Figure 1. A simplified schematic diagram of the 50.3 mm ID horizontal two-phase flow test facility with 90-degree Elbow junction (shown in top view and not scaled).

EXPERIMENTAL RESULTS

Test Conditions

In total, 15 different j_g & j_f combinations are investigated, all in bubbly two-phase flow conditions. The test conditions are labeled as Runs 1 through 15 and are summarized in Table 1. Since the local gas flow rate is a function of local pressure, the gas flow rate for each test condition is defined by the flow rate equivalent to that under the standard atmospheric pressure condition. Hence, the local volumetric gas flow rate measured at the flow meter with the back pressure, p_{back} is converted by

$$Q_{g,atm} = \frac{p_{atm} + p_{back}}{p_{atm}} Q_{g,back} \quad \text{where } p_{back} \text{ measured in acfm} \qquad (1)$$

Similarly, the local volumetric gas flow rate is calculated by

$$Q_{g,loc} = \frac{p_{atm}}{p_{atm} + p_{loc}} Q_{g,atm} \quad : \text{local gas flow rate} \qquad (2)$$

where p_{loc} is the local static pressure measured at the port of interest. Then, the local gas superficial velocity is obtained by

$$j_{g,loc} = Q_{g,loc}/A \quad : \text{local } j_g \qquad (3)$$

Table 1. Test conditions

	Run 1	Run 2	Run 3	Run 4	Run 5
$j_{g,atm}$ [m/s]*	0.116	0.124	0.127	0.312	0.320
j_f [m/s]	3.762	4.051	4.335	3.765	4.047
	Run 6	Run 7	Run 8	Run 9	Run 10
$j_{g,atm}$ [m/s]*	0.329	0.644	0.659	0.673	0.985
j_f [m/s]	4.338	3.772	4.048	4.338	3.764
	Run 11	Run 12	Run 13	Run 14	Run 15
$j_{g,atm}$ [m/s]*	1.004	1.031	1.336	1.372	1.406
j_f [m/s]	4.049	4.313	3.760	4.051	4.332

*$j_{g,atm}$ is the superficial gas velocity equivalent to the standard atmospheric pressure condition.

In view of benchmarking the reliability of local pressure measurement, the local superficial gas velocity, $\langle j_{g,loc}\rangle$ at each measurement port is compared with that calculated based on the α and u_g acquired by the conductivity probe[6]. They are found to be in relatively good agreements within $\pm 10\%$ difference as shown in Fig. 2.

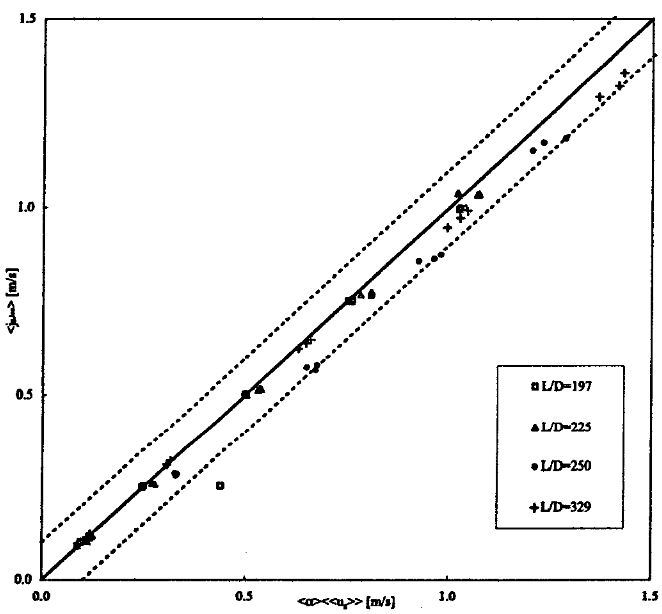


Figure 2. Comparison of the local superficial gas velocity, $\langle j_{g,loc}\rangle$ measured by flow meter with $\langle \alpha u_g\rangle$ acquired by the conductivity probe. ±10 % shown in dotted lines.

Pressure Measurements

In Fig. 3, change in pressure per unit length, *dp/dz* over the entire test section between L/D=0 and 329 is plotted with respect to the various superficial gas velocity at three different superficial liquid velocities. It is evident from the figure that the pressure loss increases with increasing gas and liquid flow rates.

In Fig. 4, the local static pressure acquired at five different axial positions along the entire test section is plotted for all flow conditions. Each figure represents pressure change at a fixed liquid flow rate with varying gas flow rates. The pressure is measured at L/D=0, 197, 225, 250 and 329, along which a 90-degree elbow is located at *L/D*=206.6. Characteristic geometrical effect of the elbow on pressure loss is clearly demonstrated in all flow conditions. It is interesting to note, however, that there is little effect in the immediate downstream of the elbow (L/D=225). The effect of elbow becomes more pronounced in the region further downstream of the elbow between L/D=225 and 250, and it is characterized by a drastic loss in pressure in that region. As the flow develops after L/D=250 into further downstream (L/D=329), the effect of elbow diminishes, and the pressure drop slope almost recovers to its initial slope before the elbow.

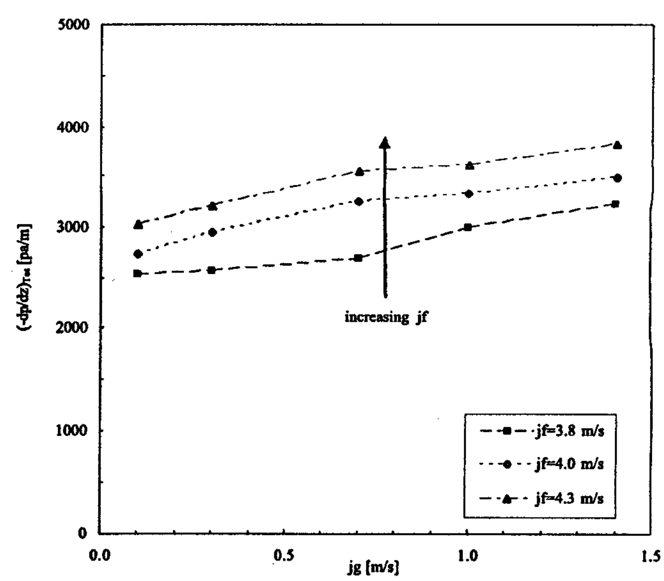


Figure 3. Pressure drop per unit length across the entire test section between *L/D*=0 and 329 for different superficial gas and liquid velocities.

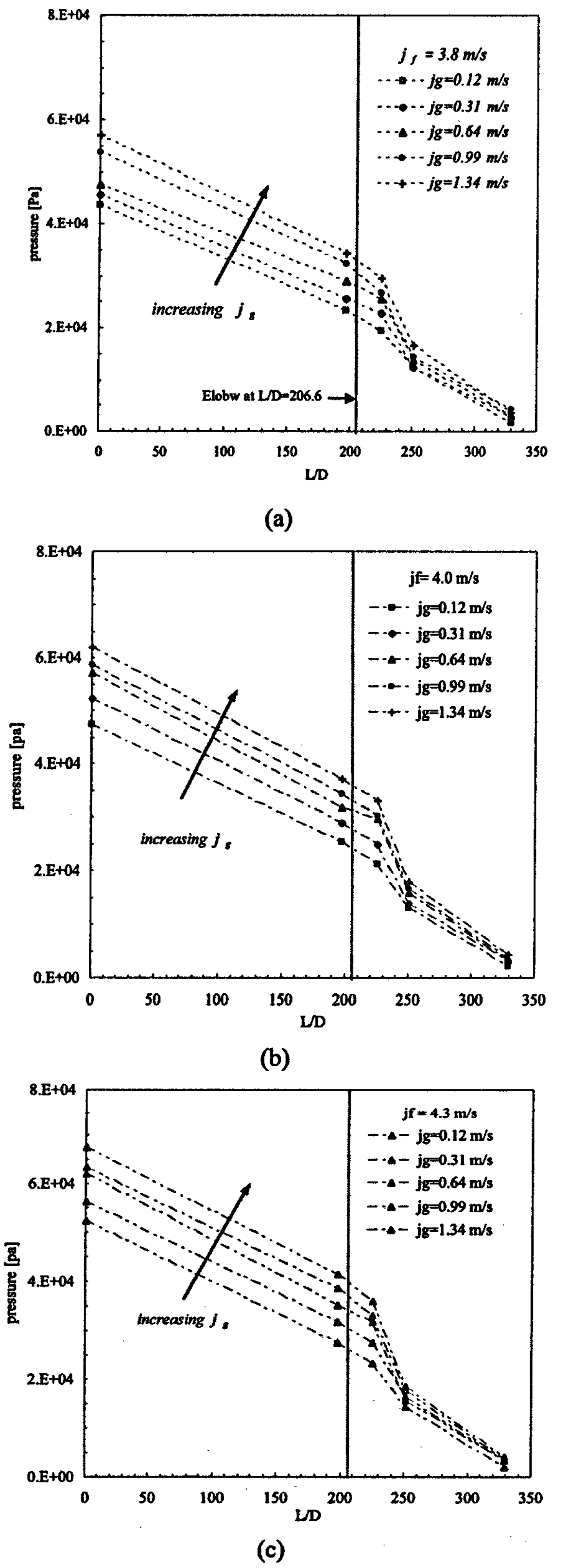


Figure 4. Change in local gage pressure measured along the axial direction of the flow.

PRESSURE LOSS CORRELATION FOR 90-DEGREE ELBOW

In general, the two-phase frictional pressure drop is correlated by the Lockhart and Martinelli correlation given by[7]

$$\phi_f^2 = 1 + \frac{C}{X} + \frac{1}{X^2} \tag{4}$$

where ϕ_f^2 and X, are two-phase frictional multiplier and Martinelli parameter, respectively. They are defined by

$$\phi_f^2 \equiv \frac{\left(\frac{dp}{dz}\right)_F^{2\phi}}{\left(\frac{dp}{dz}\right)_F^{f}} \quad \text{and} \quad X^2 = \frac{\left(\frac{dp}{dz}\right)_F^{f}}{\left(\frac{dp}{dz}\right)_F^{g}} \tag{5}$$

In Eq. (5), superscripts f, g and 2ϕ are the phase indices for liquid, gas and two-phase mixture, respectively, and subscript F indicates the frictional loss. Hence, $\left(\frac{dp}{dz}\right)_F^{f}$, $\left(\frac{dp}{dz}\right)_F^{g}$ and $\left(\frac{dp}{dz}\right)_F^{2\phi}$ in Eqs. (4) and (5) denote the frictional pressure drop due to the single-phase liquid, single-phase gas and the two-phase mixture, respectively. Here, the pressure drop due to the k^{th} phase is given in terms of the friction factor, f such that

$$\left(\frac{dp}{dz}\right)_F^{k} = \frac{2f}{D}\rho_k j_k^2 \text{ where the subscript } k = f \text{ or } g \tag{6}$$

Here, the friction factor is obtained by the Blasius formulation by:

$$f = m\,\mathrm{Re}^{-n} \text{ with } \mathrm{Re} = \frac{\rho_k j_k D}{\mu_k} \tag{7}$$

where the subscript $k = f$ or g, and the coefficients m and n for the round pipe flow are given by

$$\begin{aligned} &m = 64 \;\&\; n = 1 && \text{: for laminar flow} \\ &m = 0.079 \;\&\; n = 0.25 && \text{: for turbulent flow} \end{aligned} \tag{8}$$

Therefore, by finding appropriate values for the parameter C in Eq. (4), one can estimate the two-phase frictional pressure loss. The parameter C for the gas-liquid two-phase flow in straight horizontal pipe without any flow obstructions are given by Chishlom[8] and summarized in Table 2.

In two-phase flow through a channel with flow restriction, however, additional pressure loss stemming from the geometric effect of the restriction needs to be considered and Eq. (4) is no longer applicable. Therefore, present study develops a simple correlation accounting for the minor loss by employing similar approach as that of Lockhart and Martinelli's

Table 2. Suggested values for parameter C in Eq (4)[8]

Liquid – Gas	C
Turbulent – Turbulent (tt)	20
Turbulent – Laminar (tl)	12
Laminar – Turbulent (lt)	10
Laminar – Laminar (ll)	5

First, it is noted that Eq. (4) originates from the hypothesis that two-phase frictional pressure drop can be expressed by the pressure drop caused by each phase and its combination by:

$$\left(\frac{dp}{dz}\right)_F^{2\phi} = \left(\frac{dp}{dz}\right)_F^{f} + \left(\frac{dp}{dz}\right)_F^{g} + C\left[\left(\frac{dp}{dz}\right)_F^{f} \cdot \left(\frac{dp}{dz}\right)_F^{g}\right]^{1/2} \quad (9)$$

Since Eq. (9) is written for the flow through pipes without any minor loss, it does not account for the effect of flow restriction in two-phase pressure drop. When there is a flow restriction in a two-phase flow system, however, the total frictional pressure drop should account for losses due to both the friction and the restriction (or minor loss). Hence, the liquid-only frictional pressure drop is given by

$$\left(\frac{dp}{dz}\right)_F^{f} = \left(\frac{4f}{D} + \frac{k}{L}\right)\frac{\rho_f j_f^2}{2} \text{ with a flow restriction} \quad (10)$$

where the second term in the parenthesis in the RHS of the equation is due to the minor loss, and k and L are the minor loss factor and characteristic length scale of the restriction specific to the restriction geometry, respectively. Hence, Eq. (10) can be broken into two terms such that:

$$\left(\frac{dp}{dz}\right)_F^{f} = \left(\frac{dp}{dz}\right)_{Ff}^{f} + \left(\frac{dp}{dz}\right)_{FM}^{f} \quad (11)$$

where $\left(\frac{dp}{dz}\right)_{Ff}^{f}$ and $\left(\frac{dp}{dz}\right)_{FM}^{f}$ denote the contributions from frictional loss by the liquid phase and loss due to the flow restriction, respectively.

Assuming that the change in gas-phase frictional pressure drop is negligibly small compared to that by the liquid-phase regardless of the existence of flow restriction, the Martinelli Parameter given by Eq. (5) is redefined in two ways as:

$$X^2 = \frac{\left(\frac{dp}{dz}\right)_{Ff}^{f}}{\left(\frac{dp}{dz}\right)_F^{g}}, \text{ and} \quad (12)$$

$$X_M^2 \equiv \frac{\left(\frac{dp}{dz}\right)_{Ff}^{f}}{\left(\frac{dp}{dz}\right)_{FM}^{f}}. \quad (13)$$

Eq. (12) is essentially same as Eq. (5) and represents the contribution in the frictional pressure loss by the liquid-only flow with respect to the gas-only flow without including the minor loss. A new parameter X_M^2 given by Eq. (13), on the other hand, reflects the contribution due to the flow restriction. Furthermore, the ratio between the two parameters, X and X_M is defined for convenience as:

$$\mu^2 \equiv \frac{X^2}{X_M^2} = \frac{\left(\frac{dp}{dz}\right)_{FM}^{f}}{\left(\frac{dp}{dz}\right)_F^{g}}, \quad (14)$$

Now, combining Eq. (9) with Eqs. (12) through (14), a new Lockhart-Martinelli's correlation accounting for both the frictional and minor losses is obtained as:

$$\phi_{fM}^2 = 1 + \frac{C}{X}\left[1 + \frac{1}{X_M^2}\right]^{1/2} + \frac{\left(1+\mu^2\right)}{X^2} \quad (15)$$

where ϕ_{fM}^2 is a new two-phase friction multiplier that accounts for the minor loss. Therefore, by finding the parameter C that fits best with experimental data, the two-phase frictional pressure drop accounting for both friction and minor losses can be estimated. Furthermore, the minor loss factor k can be obtained for a given flow restriction geometry by noting that

$$X_M^2 = 4\left(\frac{f}{k}\right)\left(\frac{L}{D}\right)_{Restriction}, \quad (16)$$

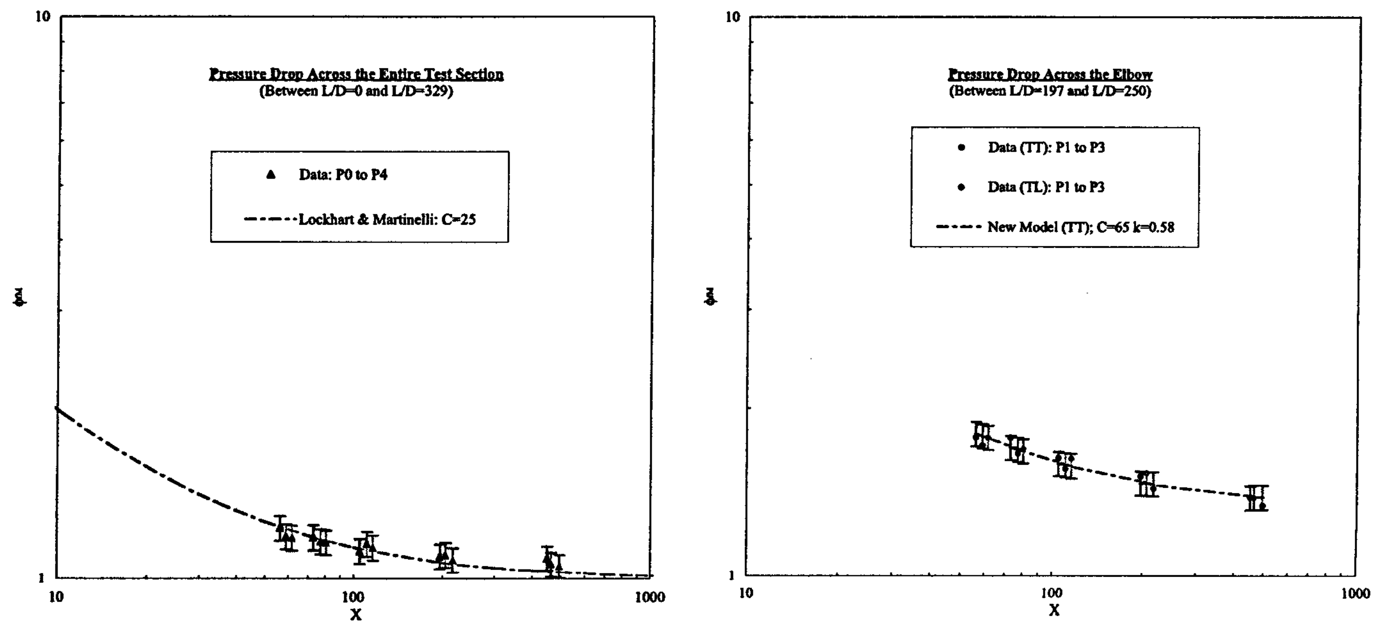
where $\left(L/D\right)_{Restriction}$ is specified by the restriction geometry, and f is given by Eq. (7).

In the present study. Eqs. (15) and (16) are employed to obtain coefficients, C and k by plotting the logarithmic graph of ϕ_{fM} versus X. The results are presented in Figs. 5(a) and 5(b). In Fig. 5(a), pressure drop across the entire test section (L/D=0 to 329) is correlated by the conventional Lockhart-Martinelli's correlation given by Eq. (4). In Fig. 5(b), pressure drop across the elbow (L/D=197 to 250) is correlated by the newly developed correlation given by Eq. (15). In this plot, both C and k (or X_M^2) are varied to find the best fit to the experimental data. In determining the parameters, it is noted that the parameter C essentially determines the slope of the asymptotic profile of $\ln\left(\phi_{fM}\right)$, and the k-factor determines the level of its asymptotic value. Therefore, the optimal value for

C is found first, then the k-factor is varied to find the best fit to the data.

In calculating the Martinelli parameter X, in the present analysis, correlation for turbulent flow is employed for the friction factor f, regardless of the gas flow rate whether it is laminar or turbulent. Namely, Eq. (7) with m=0.079 and n=0.25 is used to calculate f. This is because, in bubbly two-phase flow, the transport of dispersed gas phase is determined essentially by the liquid phase. Since all of the liquid flow rates in the present test conditions indicate that the flow is turbulent, turbulent flow correlation is employed to calculate the friction factors for both gas and liquid phases. Furthermore, the present model is correlated based on the pressure drop between the ports P1 and P3 (instead of P1 and P2). P1 is located 9.5 diameter upstream of the elbow, and P2 and P3 are located 18.1D and 43.9D downstream of the elbow, respectively. This is essentially because it is found from the experiment that the most significant pressure drop occurs across P1 and P3, instead of the P1 and P2 in all of the test conditions as shown in Fig. 4. Therefore, the present analysis is based on $(L/D)_{Elbow}$=53.5

Fig. 5(a) shows that the pressure drop across the entire test section can be predicted well by the conventional Lockhart-Martinelli's correlation with C=25, which is slightly higher than the recommended value of C=20 developed for turbulent-turbulent gas-liquid two-phase flow through straight flow channel without flow restriction. In Fig. 5(b), the newly developed correlation with modified parameter, C=65 and k=0.58 is plotted with the experimental data. The present model predicts the data quite well with an average percent difference of only 2%. The two-phase minor loss factor, k=0.58 acquired by the correlation is approximately 50% higher than k=0.39 recommended for single-phase flow[9].



(a) (b)

Figure 5. The two-phase frictional multiplier ϕ_{fM} with respect to the Martinelli parameter X for the bubbly air-water two-phase flow in horizontal tube of 50.3 mm ID with 90-degree Elbow. (a) Prediction made by the conventional Lockhart-Martinelli's correlation for pressure drop across the entire test section (b) Prediction made by the new correlation for pressure drop across the elbow, between P1 and P3 (or L/D=197 and 250). Error bar shown: ±5%.

SUMMARY AND DISCUSSION

In summary, following discussions can be made based on the present results:

(1) The geometric effect of 90-degree elbow is well demonstrated in the experimental data. Additional pressure loss due to the minor loss across the elbow is clearly characterized by steeper slope in the plot of pressure loss versus development length. It is also shown that the pressure drop increases with increasing gas and liquid flow rates.

(2) The effect of elbow on pressure drop is found to be more pronounced further downstream of the elbow than immediate downstream of the elbow.

(3) The pressure drop across the entire test section matches well with the existing Lockhart-Martinelli's correlation with C=25. The higher value of C=25 compared to the conventional value of C=20 is due to the remaining effect

of elbow. It is evident from Fig. 4 that the slope in pressure drop (i.e., dp/dz) between L/D=250 and 329 in all flow conditions is not fully recovered to their initial slope before the elbow, between L/D=0 and 197. It implies that the flow is yet to be fully recovered from the elbow effect even after 122.7 diameters downstream of the elbow.

(4) The newly developed correlation, given by Eq. (15) matches well with the experimental data when the minor loss factor k=0.58 and C=65 are employed. The significantly higher value of C=65 compared to the conventional value of C=20 indicates geometric effect of the elbow on two-phase frictional pressure loss. The minor loss factor, k=0.58 is approximately 50% higher than the conventional k-factor, k=0.39 recommended for the single-phase flow through the regular 90-degree (flanged) elbow. This signifies the additional pressure loss due to the two-phase flow around the bend. The present correlation matches very well with the data with an average percent difference of only 2%.

(5) The current model needs to be verified by additional experimental data. The present model is developed based on the pressure measurement across ports P1 and P3, instead of ports P1 and P2 because the most significant pressure loss occurs across P1 and P3. P3 is located far downstream of the Elbow ($(L/D)_{Elbow}$=43.9) and may not reflect the actual pressure drop at the elbow.

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