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An investigation and comparative study of the pressure drop in air–water two-phase flow in vertical helicoidal pipes

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Abstract—In this paper, an experimental investigation and comparative study were performed on the pressure drop and void fraction of air–water two-phase flow in vertical helicoidal pipes. Eight coils have been tested. The results show that the pressure drop of the two-phase flow in vertical helicoidal pipes depends on both the Lockhart–Martinelli parameter and the flow rates for low flow rates in small ratio of coil diameter to pipe diameter. The geometric parameters have no apparent effects on the void fraction, but they do affect the frictional pressure drop. Finally, the correlation for frictional pressure drop multiplier for small coils is provided based on the experimental data.

1. INTRODUCTION

Because of the high efficiency in heat transfer and compactness in volume, helicoidal pipes are used extensively in heat exchangers, nuclear reactors, chemical plants, and the food, drug and cryogenics industries, as well as in military devices. Both single-phase and two-phase flow can occur in helicoidal pipes, depending on specific applications. For design purposes, it is important to know the pressure drop in both single or two-phase flow. Therefore, extensive studies on the flow and heat transfer in helicoidal pipes have been conducted for several decades. The investigation of two-phase flow in helicoidal pipes is insufficient, compared to the investigation of single-phase flow. Most publications on single-phase flow in curved ducts have been reviewed by Berger and Talbot [1] and Shah and Joshi [2]. It is well known that the secondary flow due to centrifugal force and torsion force in the cross section of the helicoidal pipe is a significant factor affecting the flow phenomena, consequently affecting the frictional pressure drop and heat transfer in both single-phase and two-phase flow.

Although different flow characteristics exist between two-phase flow in the straight pipe and the helicoidal pipe, the method for analyzing the pressure drop data for the straight pipe is still used or modified to describe two-phase flow in helicoidal pipes. Rippel *et al.* [3] worked on the two-phase flow of gas and liquid in a helicoidal pipe with an i.d. of 12.7 mm and a coil diameter of 208 mm. The experimental fluids were air–water, helium–water, Freon-12–water, and air–2-propanol. The pressure drop data was compared with the Lockhart–Martinelli correlation for a straight pipe [4]. It was found that the result satisfied the Lockhart–Martinelli correlation moderately with precision values of about 40%. Some effects of the liquid flow rate can be seen in their figures where liquid the flow rate is lower. Since the tube's diameter is small in size, these effects were not significant. Comprehensive research on two-phase flow in helical coils was reported by Banerjee *et al.* [5]. Measurements were conducted for coils with different pipe and coil diameters to determine the pressure drop, void fraction and the flow patterns encountered. The Lockhart–Martinelli correlation was slightly modified and was found to satisfy the data system. It was discovered that the helix angle, if small, appears to have no discernible effect on the pressure drop. Boyce *et al.* [6] measured the pressure drop of two-phase flow in helical coiled plastic tubes of 31.75 mm i.d. and different coil diameters. It was indicated that the pressure drop data was adequately correlated by the Lockhart–Martinelli relationship and corresponded with the findings of Rippel *et al.* [3] and Banerjee *et al.* [5]. The Lockhart–Martinelli method was also used to correlate the pressure drop data of convection boiling [7] and downward two-phase flow [3] in vertical helicoidal pipes. Several other methods and correlations were proposed to determine the pressure drop data for two-

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NOMENCLATURE

b	pitch of the coil [m]		Greek symbols	
D	coil diameter (center to center) [m]		α	void fraction
De	Dean number		β	helix angle
d	pipe diameter [m]		Δp	pressure drop
f	friction factor		μ	dynamic viscosity [N s m^{-2}]
Fr	Froude number		ϕ	pressure drop multiplier
g	gravitational acceleration [m s^{-2}]		ρ	density [kg m^{-3}].
m	constant			
n	coil turns		Subscripts	
p	pressure [Pa]		a	acceleration pressure gradient
Re	Reynolds number		f	friction
U	superficial velocity [m s^{-1}]		G	gas
W	mass of the water [kg]		g	gravitation
X	Lockhart–Martinelli parameter		L	liquid
z	distance along the flow direction [m].		S	straight pipe
			TP	two-phase.

phase flow in vertical helicoidal pipe. Akagawa *et al.* [8] presented the frictional pressure drop, void fraction, and flow patterns of air–water two-phase flow in a helicoidal pipe. It was indicated in their experimental range that the frictional pressure drop of the two-phase flow in these coils is 1.1–1.5 times as much as that in a straight pipe. Three types of empirical equations for the frictional pressure drop were proposed, and the experimental data was correlated by a modified Lockhart–Martinelli approach independent of the pipe diameter to coil diameter ratio. Kasturi and Stepanek [9] used air–water, air–corn-sugar-water, air–glycerol-water and air–butanol–water solutions in their experiments to measure the pressure drop. The data was compared with the Lockhart–Martinelli correlation and Dukler's correlation [10]. They determined the Lockhart–Martinelli correlation better conformed to the data than Dukler's correlation, but there was a systematic displacement of the curves for various systems with the Lockhart–Martinelli plot. Therefore, in their second paper [11], the correlations for the pressure drop were reported in terms of new corresponding parameters that consist of a combination of known dimensionless groups, and were obtained using the separated flow model. It was observed that the experimental data obtained for the helicoidal pipe agreed with the correlation, except at high liquid flow rates, and the data of other investigations are well represented by the correlation established. In the work of Rangacharyulu and Davies [12], a new correlation for a two-phase flow frictional pressure drop was proposed based on a modified extension of the Lockhart–Martinelli theory. The experimental data interacts well in terms of dimensional groups other than the Lockhart–Martinelli correlation. Chen and Zhou [13] obtained their frictional pressure drop correlation for air–water two-phase flow in the helicoidal pipe using the dimension analysis theory. One correlation for the prediction of a two-phase friction factor was provided by these authors. Mujawar and Rao [14] extended the Lockhart–Martinelli approach for air–water and gas–non-Newtonian liquid (power law type) two-phase flow in a helicoidal pipe. It was shown that the two-phase flow pressure drop was successfully correlated by the Lockhart–Martinelli method if the flow patterns were specified. Recently, Saxena *et al.* [15] proposed another method to correlate the pressure drop data obtained in two-phase flow in a helicoidal pipe. The proposed model retains the identity of each phase and separately accounts for the effects of curvature and tube inclination resulting from the torsion of the tube. This makes it possible to use a single model to predict pressure drop for both upward and downward two-phase flow in a helicoidal pipe.

Although as discussed above, most of the pressure drop data of two-phase flow in vertical helicoidal pipe could be represented by the Lockhart–Martinelli correlation where the pressure drop multiplier is the function of the Lockhart–Martinelli parameter, some effects of the liquid velocity on the pressure drop were also observed from the data. Boyce *et al.* [6] noted that the data for each liquid flow rate lies on a separate line with little scatter, even the agreement between their data and the Lockhart–Martinelli correlation is about the same as that usually found for two-phase flow in straight pipe. Banerjee *et al.* [5] also gave a figure to show the effect of liquid velocity on the pressure drop multiplier, especially for the low gas and liquid velocities. In addition, Hart *et al.* [16] reported that the axial pressure drop of two-phase flow in the helicoidal pipe increased as a function of the volume flow rate of gas, but no attempt has been made to correlate the data. Therefore, further investigation is needed to verify and evaluate existing data and correlations to account for the effect of the liquid velocity. In this paper, an experimental investigation and comparative study of air–water two-phase flow in vertical helicoidal pipes have been performed. The pressure drop and void fraction have been measured for different configurations of the vertical helicoidal pipes.

2. THE EXPERIMENTAL APPARATUS

2.1. *Experimental system*

The experiments were done in an air–water two-phase flow and heat transfer system, which includes an air–water flow loop, test sections, and associated instrumentation. A detailed description of the flow loop was given in our previous work [17] and will not be repeated here.

The test section is shown in Fig. 1. The helical pipe was made by wrapping a Tygon tube (transparent plastic tube with strengthen fabric for larger tube diameter) around a circular concrete form. Four different inside diameters of the tube (12.7 mm, 19.1 mm, 25.4 mm and 38.1 mm) and two different outside diameters of the concrete cylindrical forms (305 mm and 609 mm) were used to construct the helicoidal pipes with different configurations. The helical pipe was then fixed and tightened by clamps. The entire test section was vertically mounted on a UNISTRUT frame to reduce vibration. Because water was constantly flowing in the bottom portion of the helicoidal pipe and the collection tube lines, between the taps and the pressure transducer, were filled with water, the pressure difference was measured by a differential pressure transducer (wet/wet). Also, the pressure of the air–water mixture was measured at the inlet of the separator. Therefore, the absolute average pressure in the test section was calculated, which was used to determine the thermal properties of air in the test section. The void fraction was measured by a quick shut valve method, which was achieved by mounting three solenoid valves in the test section, which are shown in Fig. 1 as V-1, V-2 and V-3. During the experiment, valves V-1 and V-2 are open and the by-pass valve V-3 is closed. After the flow becomes steady, V-1 and V-2 are closed and V-3 is opened simultaneously. The water trapped in the test section between V-1 and V-2 is the water hold-up which is purged out and weighed by a calibrated electronical scale.

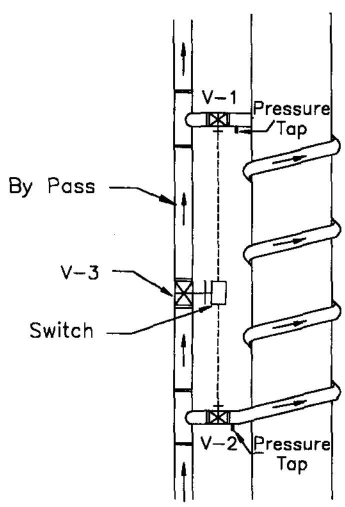


Fig. 1. Test section.

The experimental system has been verified by experiments of single-phase and two-phase flow in straight pipes and single-phase flow in helicoidal pipes. The results have been compared [17] with some correlations in the literature. The pressure drop and void fraction of the air–water two-phase flow in the helicoidal pipes were then measured in the regions of the superficial velocities of water and air, 0.008–2.2 m s^{-1} and 0.2–50 m s^{-1}, respectively.

2.2. *Experimental uncertainty analysis*

The quantities measured directly are the flow rates, pressure drop and mass of water. Both the air and water flow rates were measured by three Fisher and Porter rotameter-type flow meters with an accuracy of $\pm 2\%$. The pressure drop was measured by two Rosemount pressure transducers with an accuracy of $\pm 2\%$. The water mass was measured by an electronic scale with an accuracy of 1%. The accuracy of other quantities, such as length and properties, was estimated at 1% and 0.25%, respectively. Analyses of the uncertainties of ϕ_L or ϕ_G and X were conducted throughout the experiments, using the method recommended by Kline and McClintock [18] and Moffat [19]. It was estimated that the uncertainties of ϕ_L and ϕ_G were 5.14% and the uncertainty of X was 9.2% for most experimental cases, except a few cases of very low flow rates near the low reading limits of the flow meter. In addition, the uncertainty of the void fraction was estimated to be less than 6%.

3. RESULTS AND DISCUSSION

For comparison, the Lockhart–Martinelli method is applied in the data reduction of the two-phase flow. From the theory of separated flow models, it is assumed that the pressure drops in the water phase and the air phase are equal; and also equal to the two-phase pressure drops. The general equation for the pressure drop gradient in two-phase flow is:

$$\left(\frac{dp}{dz}\right)_{TP} = \left(\frac{dp}{dz}\right)_{TPf} + \left(\frac{dp}{dz}\right)_{TPa} + \left(\frac{dp}{dz}\right)_{TPg} \quad (1)$$

where $(dp/dz)_{TPf}$ is the frictional pressure gradient, $(dp/dz)_{TPa}$ is the acceleration pressure gradient and $(dp/dz)_{TPg}$ is the gravitational pressure gradient. Owing to no phase change, the accelerative effects are ignored. Any interaction between the air and water phases is neglected. Therefore, the frictional pressure gradient can be obtained as follows:

$$\left(\frac{dp}{dz}\right)_{TPf} = \left(\frac{dp}{dz}\right)_{TP} - \left[\frac{dp}{dz}\right]_{TPg} \quad (2)$$

and $(dp/dz)_{TPg}$ is calculated from void fraction data by the equation below:

$$\left(\frac{dp}{dz}\right)_{TPg} = \rho_L g \tan(\beta)(1-\alpha). \quad (3)$$

The frictional pressure gradient in two-phase flow, $(dp/dz)_{TPf}$, is related to that of gas or liquid phases flowing in helicoidal pipes with the help of the Lockhart–Martinelli method. Thus, the present data is presented in terms of pressure drop multipliers, ϕ_G and ϕ_L, vs the Lockhart–Martinelli parameter, X, which are defined as the following:

$$\phi_G^2 = (dp/dz)_{TPf}/(dp/dz)_G \quad (4)$$

$$\phi_L^2 = (dp/dz)_{TPf}/(dp/dz)_L \quad (5)$$

and

$$X^2 = (dp/dz)_L/(dp/dz)_G. \quad (6)$$

The pressure gradient in the single-phase flow used in equations (4) and (5) or (6) can be obtained from the following equations:

$$\left(\frac{dp}{dz}\right)_G = 2f_G\rho_G U_G^2/d \quad (7)$$

$$\left(\frac{dp}{dz}\right)_L = 2f_L\rho_L U_L^2/d \quad (8)$$

and the pressure gradient in the two-phase flow, $(dp/dz)_{TP}$, is computed from the measured pressure drop data, which is:

$$\left(\frac{dp}{dz}\right)_{TP} = \frac{\Delta p}{\pi D n/\cos\beta} \quad (9)$$

where D, n and β are coil diameter, coil turns, and helix angle, respectively. Δp is the pressure drop reading between the two pressure taps. For laminar flow, the friction factors, f_G and f_L, for single-phase flow in the helicoidal pipes are obtained from the equation by Manlapaz and Churchill [20],

$$\frac{f}{f_S} = \left[\left(1.0 - \frac{0.18}{[1+(35/De)^2]^{0.5}}\right)^m + \left(1.0 + \frac{d/D}{3}\right)^2\left(\frac{De}{88.33}\right)\right]^{0.5} \quad (10)$$

where $m = 2$ for $De < 20$, $m = 1$ for $20 < De < 40$, $m = 0$ for $De > 40$ and $f_S = 16/Re$.

For turbulent flow, the equation by Ito [21] is applied to calculate the friction factor:

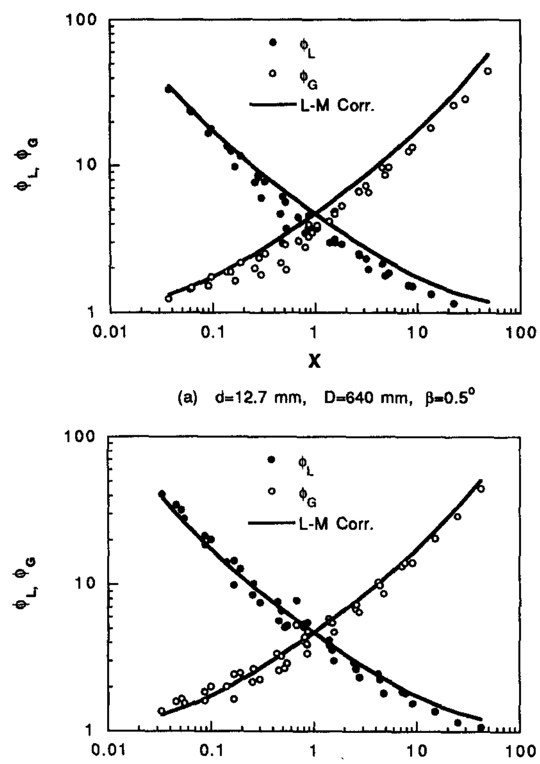
$$f\left(\frac{D}{d}\right)^{0.5} = 0.00725 + 0.076\left[Re\left(\frac{D}{d}\right)^{-2}\right]^{-0.25} \quad (11)$$

for $0.034 < Re(D/d)^{-2} < 300$. The Reynolds number and Dean number in equations (10) and (11) are defined as:

$$Re = \frac{\rho U d}{\mu} \quad \text{and} \quad De = Re\left(\frac{d}{D}\right)^{1/2}. \quad (12)$$

3.1. *Large coils*

In Figs. 2–5, the pressure drop multipliers for vertical helicoidal pipes with larger coil diameters are illustrated in terms of the Lockhart–Martinelli parameter and the Reynolds number. In each figure, the measurements are shown for two helix angles of helicoidal pipes with the same tube diameter. Also, the Lockhart–Martinelli correlation for two-phase flow in straight pipes is depicted with a solid line in each figure. Figure 2 shows the results for the helicoidal pipes with the 12.7 mm tube diameter. The helix angles are 0.5 and 10°, respectively. It is evident that the data is close or falls close to the Lockhart–Martinelli correlations. The pressure drop multipliers depend



(a) d=12.7 mm, D=640 mm, β=0.5°

(b) d=12.7 mm, D=640 mm, β=10°

Fig. 2. ϕ_L and ϕ_G vs X for large coils with a tube diameter of 12.7 mm.

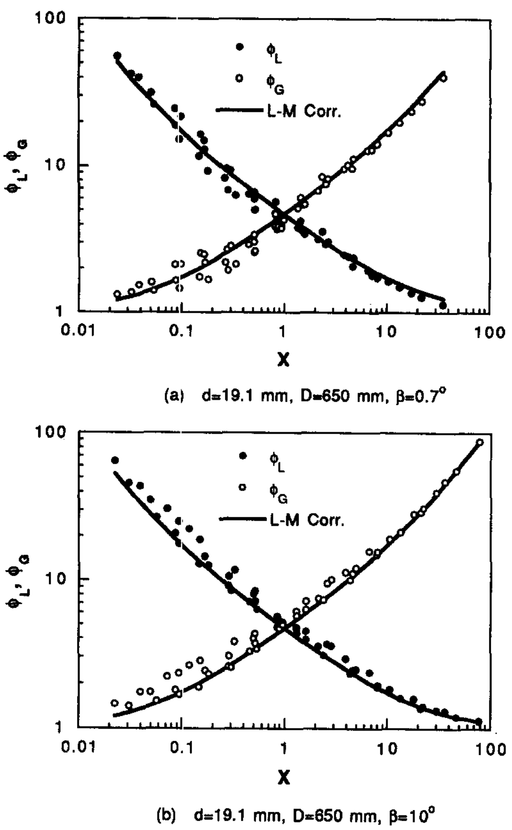


Fig. 3. ϕ_L and ϕ_G vs X for large coils with a tube diameter of 19.1 mm.

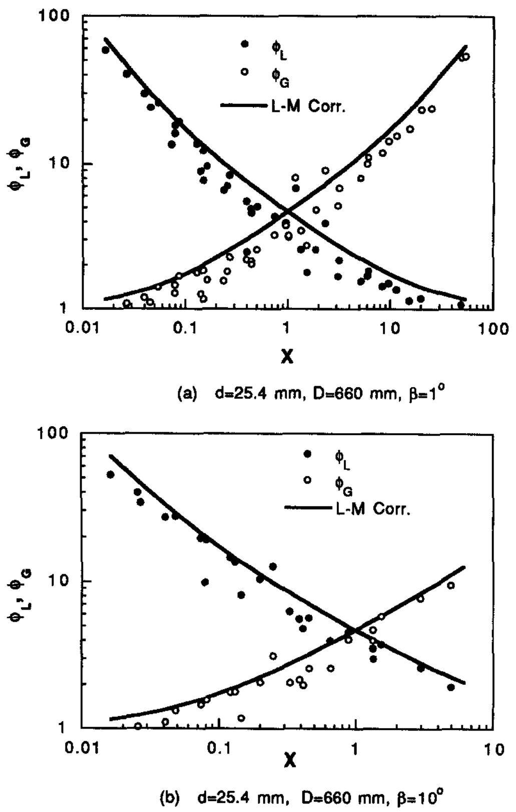


Fig. 4. ϕ_L and ϕ_G vs X for large coils with a tube diameter of 25.4 mm.

solely on the Lockhart–Martinelli parameter. The same phenomena can be seen in Fig. 3 for the helicoidal pipes with a tube diameter of 19.1 mm and Fig. 4 for the helicoidal pipes with a tube diameter of 25.4 mm. The Lockhart–Martinelli correlation adequately represent the data from the corresponding measurements. However, different tendencies are present for the pressure drop multipliers vs the Lockhart–Martinelli parameter for the helicoidal pipes with a tube diameter of 38.1 mm (Fig. 5). The data no longer remains close to the Lockhart–Martinelli predictions. It is obvious that the pressure drop multiplier not only depends on the Lockhart–Martinelli parameter, but also depends on the liquid Reynolds number. Similar data has been obtained in the measurement of two helicoidal pipes with different helix angles [Fig. 5(a) and (b)].

3.2. *Small coils*

The variations of the pressure drop multipliers with the Lockhart–Martinelli parameter for the vertical helicoidal pipes with small coil diameters are displayed in Figs. 6–9. Two helix angles are considered in the experiments for the helicoidal pipes with the same tube diameter. In Fig. 6, the results are shown for the helicoidal pipe with a tube diameter of 12.7 mm. Figure 6(a) presents the helix angle of 1°, and Fig. 6(b) depicts the helix angle of 10°. The major difference between the two graphs is that when the helix angle of the helicoidal pipe is larger, the pressure drop multipliers are related to both the Lockhart–Martinelli parameter and the Reynolds number. As the Reynolds number increases, the pressure drop multipliers are closer to the Lockhart–Martinelli correlations. Furthermore, the results for the vertical helicoidal pipes with tube diameters of 19.1, 25.4 and 38.1 mm are illustrated in Figs. 7–9. It is easily seen that their common feature is the pressure drop multiplier's dependence on the flow rate, despite the different geometric configurations of the helicoidal pipes. It is also noted that the divergence from the Lockhart–Martinelli correlation is more prominent with increases of the tube diameter and helix angle of the helicoidal pipes.

3.3. *Void fraction*

As indicated, the void fraction of the two-phase flow in the vertical helicoidal pipe is measured by the quick shut-off method. The definition used in the present investigation of void fraction is:

$$\alpha = 1 - \frac{W_{TP}}{W} \tag{13}$$

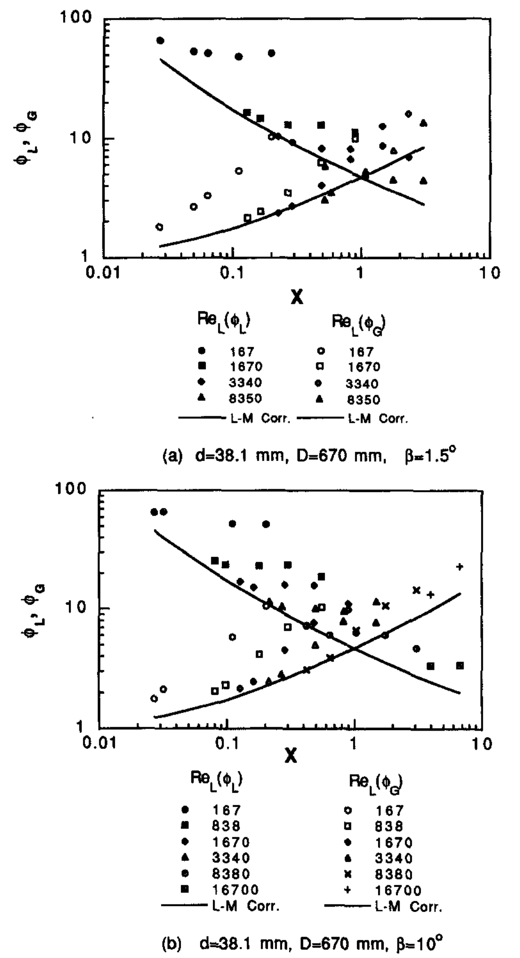


Fig. 5. ϕ_L and ϕ_G vs X for large coils with a tube diameter of 38.1 mm.

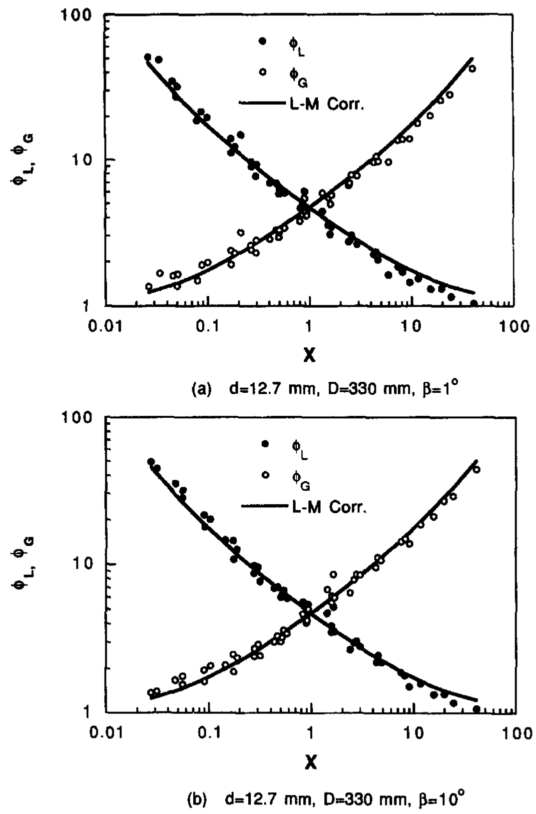


Fig. 6. ϕ_L and ϕ_G vs X for small coils with a tube diameter of 12.7 mm.

where α is the void fraction, W_{TP} is the mass of the water hold-up in the two-phase flow, and the W represents the maximum mass of water the helicoidal pipe can hold.

Figure 10 depicts the typical measurement of the void fraction. The corresponding parameters used in the experiment are given in each graph. It can be observed that the void fraction data is closer to the solid line, which is the Lockhart–Martinelli prediction of the void fraction of two-phase flow in a straight pipe, when the Lockhart–Martinelli parameter is smaller. Some divergence is evident in the case of a larger value of the Lockhart–Martinelli parameter. This conclusion is valid for all the cases in our experimental measurements. Therefore, the effects of the coil diameter and helix angle on the void fraction can be ignored.

3.4. *Comparison*

As mentioned in the introduction, the previous studies [5, 6] indicated that the Lockhart–Martinelli correlations for the straight pipe can be used to predict the pressure drop in the two-phase flow in helicoidal pipes. However, besides the effect of the Lockhart–Martinelli parameter, the obvious effect of flow rates on the pressure drop multiplier have been observed in present experiments. A comparison of some of the present results with Banerjee *et al.* [5] has been given in Fig. 11, and the comparison with Boyce *et al.* [6] is provided in Fig. 12.

3.5. *Correlation*

Based on the present experimental data, the correlation of frictional pressure drop in two-phase flow in vertical helicoidal pipes is developed for small coil diameters. Examining the experimental data reveals that when liquid and gas velocities are higher, the data points are on the line of the Lockhart–Martinelli correlation. Therefore, the pressure drop multiplier ratio between the experimental value to that calculated from the Lockhart–Martinelli correlation is used in the correlation. For the two-phase flow in vertical helicoidal pipe, three main forces affect the flow pattern and pressure drop: the inertia force, liquid gravity force and centrifugal force. The effects of these forces can be expressed in terms of Fr, d/D and $\tan\beta$. Therefore, the ratio of the pressure drop

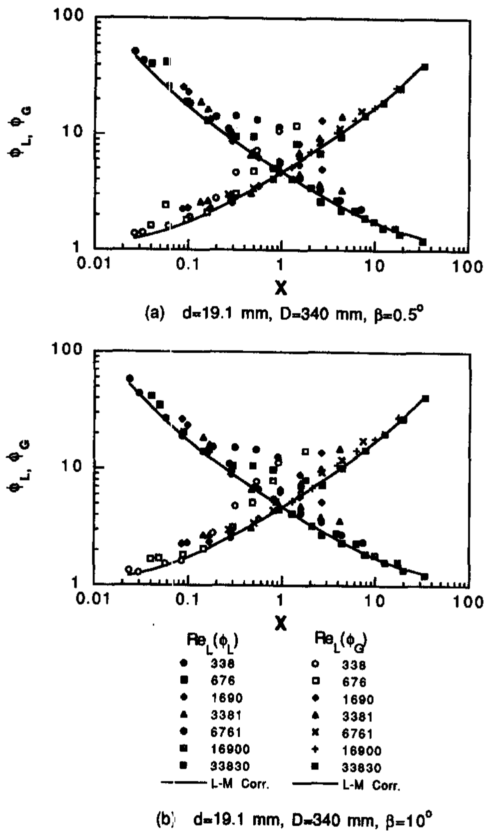


Fig. 7. ϕ_L and ϕ_G vs X for small coils with a tube diameter of 19.1 mm.

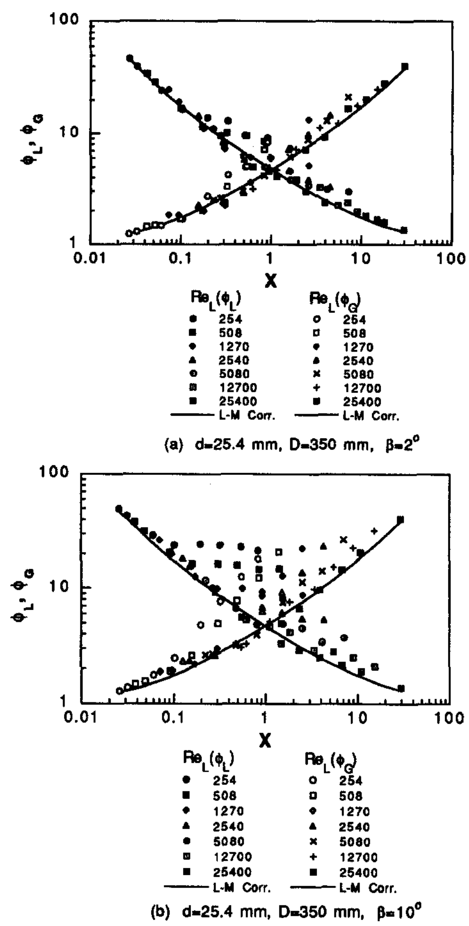


Fig. 8. ϕ_L and ϕ_G vs X for small coils with a tube diameter of 25.4 mm.

multiplier is correlated as a function of these three parameters, as well as the Lockhart–Martinelli parameter X. After trying dozens of function forms and making iterative optimization of the constant in the model, the following correlation is obtained:

$$\phi_L \Big/ \left(1+\frac{20}{X}+\frac{1}{X^2}\right)^{1/2} = 1+\frac{X}{65.45F_d^{0.6}} \qquad \text{for } F_d \leqslant 0.1 \qquad (14)$$

$$\phi_L \Big/ \left(1+\frac{20}{X}+\frac{1}{X^2}\right)^{1/2} = 1+\frac{X}{434.8F_d^{1.7}} \qquad \text{for } F_d > 0.1 \qquad (15)$$

where, F_d is defined as

$$F_d = Fr\left(\frac{d}{D}\right)^{1/2}(1+\tan\beta)^{0.2} = \frac{U_L^2}{gd}\left(\frac{d}{D}\right)^{1/2}(1+\tan\beta)^{0.2}. \qquad (16)$$

The maximum deviation between the prediction from equations (14) and (15) and the experimental data of the pressure drop multiplier (ϕ_L) is about $\pm 35\%$. As an example, the experimental data is compared with the prediction from equations (14) and (15) for the case of $d = 19.1$ mm, $D = 340$ mm and $\beta = 0.5$°C (Fig. 13). It is shown that the experimental data is closely equated, and when the liquid or gas velocity increases, the new correlations coincide with the L–M correlation.

4. CONCLUDING REMARKS

The pressure drop and void fraction of air–water two-phase flow in vertical helicoidal pipes have been measured in the present study. The Lockhart–Martinelli method was used for presenting the experimental data. The results show that the pressure drop in two-phase flow depends on both the Lockhart–Martinelli parameter and the flow rates which are represented by the superficial Reynolds number of water. The correlation of frictional pressure drop in two-phase flow in the vertical helicoidal pipes has been obtained for small coils. On the other hand, the void fraction can be predicted by the Lockhart–Martinelli

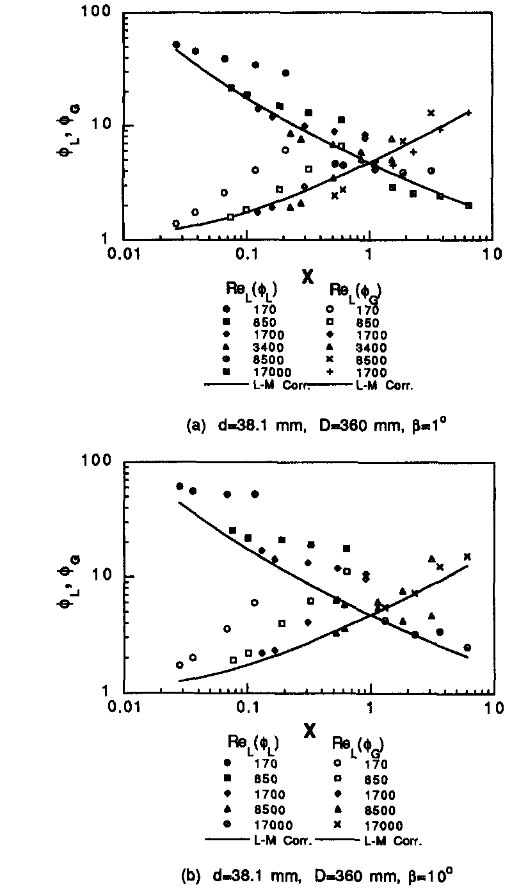


Fig. 9. ϕ_L and ϕ_G vs X for small coils with a tube diameter of 38.1 mm.

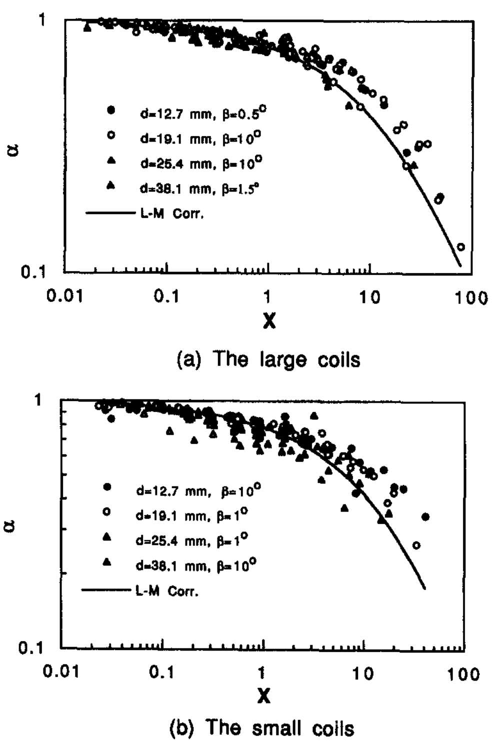


Fig. 10. Void fraction for vertical helicoidal pipes.

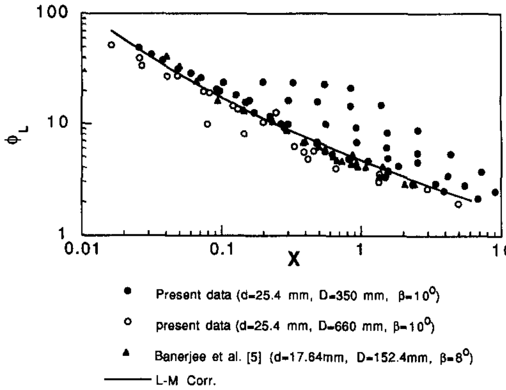


Fig. 11. Comparison of the pressure drop data with the Banerjee *et al.* [5] data.

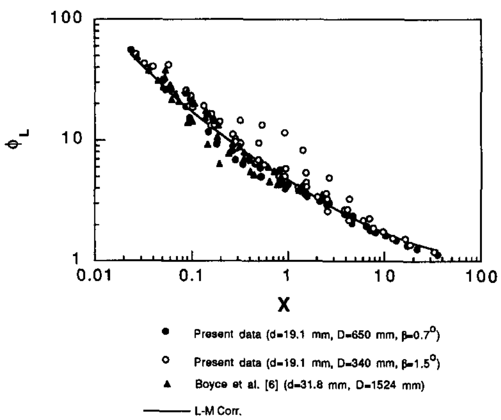


Fig. 12. Comparison of the pressure drop data with the Boyce *et al.* [6] data.

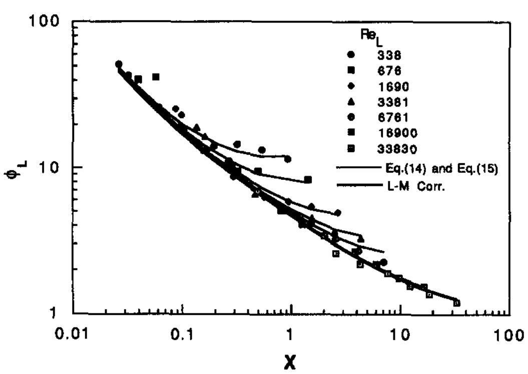


Fig. 13. Comparison between the experimental data and the correlations (d = 19.1 mm, D = 340 mm, β = 0.5°C).

correlation. It seems that the helix angle, coil diameter and pipe diameter have no apparent effect on the void fraction, but they do have some effect on the frictional pressure drop.

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