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MEASUREMENT AND CORRELATION OF THE PRESSURE DROP IN AIR–WATER TWO-PHASE FLOW IN HORIZONTAL HELICOIDAL PIPES

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Abstract—Experimental investigations are conducted for air–water two-phase flow in horizontal helicoidal pipes of varying configurations. The helicoidal pipes are constructed by wrapping Tygon tubing around cylindrical concrete forms. Four different inside diameters of tubing and two different outside diameters of the cylindrical concrete forms are used to make the helicoidal pipe with different configurations. Also, the helix angle of helicoidal pipes varies up to 20 degrees. A total of 32 helicoidal pipes has been tested for the present study. The experiments have been performed for superficial water velocity in the range of $U_L = 0.008$–2.2 m/s and superficial air velocity in the range of $U_G = 0.2$–50 m/s. The pressure drop of the air–water two-phase flow is measured and the data are well correlated. It was found that the pressure drop multiplier relates strongly to the superficial velocities of air or water, and that the helix angle has almost no effect on the pressure drop, although the pipe and coil diameters have certain effects in low rates of flow. Correlation for two-phase flow in the horizontal helicoidal pipes has been established based on the present experimental data.

Key Words: two-phase flow, pressure drop, correlation, helicoidal pipe

INTRODUCTION

Helicoidal pipes are used extensively in compact heat exchangers, boilers, refrigerators, nuclear reactors, chemical plants, as well as the food, drug and cryogenics industries. Either single-phase flow or two-phase flow can occur in helicoidal pipes, depending on specific applications. A literature survey indicates that numerous publications can be found dealing with flow phenomena and the pressure drop of single-phase flow in a helicoidal pipe (Berger & Talbot 1983). However, two-phase flow in helicoidal pipes has rarely been investigated as compared to single-phase flow studies. Among the limited investigations, most were conducted for two-phase flow in vertical helicoidal pipes. Some of the experimental results indicate that the frictional pressure drop of two-phase flow in a vertical helicoidal pipe can be predicted using the correlations for a straight pipe provided by Lockhart & Martinelli (1949). Rippel *et al.* (1966) 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. It was found that their data satisfied the correlation fairly well with values of about 40% precision. Owhadi *et al.* (1968) also found satisfactory agreement between their results of two-phase flow pressure drop in a helical coil and the Lockhart–Martinelli correlation with a modified Lockhart–Martinelli parameter. Comprehensive research on two-phase flow in a coil was reported by Banerjee *et al.* (1969). The Lockhart–Martinelli correlation was slightly modified and was found to satisfy the data. The helix angle (if small) appears to have no discernible effect on the pressure drop. Boyce *et al.* (1969) found that the Lockhart–Martinelli correlation adequately predicted the data. But in another study (Akagawa *et al.* 1971), it was confirmed that the frictional pressure drop of the two-phase flow in helicoidal pipes is 1.1–1.5 times as much as that in a straight pipe in their experimental range. Three types of empirical equations for the frictional pressure drop were proposed and also the experimental data were correlated by a modified Lockhart–Martinelli approach independent of the pipe diameter to coil diameter ratio. Kasturi & Stepanek (1972a) used air–water,

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air–corn–sugar–water, air–glycerol–water and air–butanol–water solutions in their experiments to measure the pressure drop. The data were compared with the Lockhart–Martinelli correlation and Dukler's correlation. It was found that the Lockhart–Martinelli correlation conformed to the data better than Duckler's correlation, but there was a systematic displacement of the curves for various systems with the Lockhart–Martinelli plot. Therefore, in their continued study (Kasturi & Stepanek 1972b), the correlations for the pressure drop were reported in terms of new correlating parameters that consist of a combination of known dimensionless groups and were obtained using the separated flow model. In the work of Rangacharyulu & Davies (1984), a new correlation for two-phase flow frictional pressure drop was also proposed based on a modified extension of the Lockhart–Martinelli theory. The experimental data are well correlated in terms of dimensional groups other than the Lockhart–Martinelli correlation. Chen & Zhou (1981) found that the major factors affecting the two-phase friction factor are the gas fraction, liquid Reynolds number, gas Reynolds number and the pipe to coil diameter ratios. One correlation for the prediction of a two-phase friction factor was provided by using dimension analysis. Mujawar & Rao (1981) pointed out that the two-phase flow pressure drop could be successfully correlated by the Lockhart–Martinelli method if the flow patterns were specified. In addition, Hart *et al.* (1988) reported experimentally that the axial pressure drop of two-phase flow in the helicoidal pipe increased as a function of the volume flow rate of the gas, but no attempt has been made to correlate the data. Recently, Saxena *et al.* (1990) proposed another method to correlate the pressure drop data obtained in two-phase flow in a helicoidal pipe, which retains the identity of each phase and separately accounts for the effects of curvature and tube inclination resulting from the torsion of the tube.

In summary, all of the above-mentioned previous researches are studies of two-phase flow in vertical helicoidal pipes. It seems that the Lockhart–Martinelli method is suitable for correlating the pressure drop data in certain conditions. However, pressure drop measurements and correlations have not been reported so far for two-phase flow in a horizontal helicoidal pipe, which is the motivation for the present research.

THE EXPERIMENTAL SYSTEM

The experimental system consists of an air–water flow loop, test sections and associated instrumentation. A schematic representation of the air–water flow loop is shown in figure 1. The air–water mixer is illustrated in figure 2; the air–water separator tank is shown in figure 3; and the test section is depicted in figure 4.

The water is stored in a collection tank. From there, it flows downward into the suction of a 2 Hp centrifugal pump. After exiting the pump, part of the flow passes through a water filter and the rest returns to the collection tank through a by-pass line. The water flow leaving the water filter is continuously routed to the water measuring station, where the water flow rate and pressure are measured. After measurement, the water flows directly to one of the mixers. The heat absorbed by the water due to friction pressure loss, and from the centrifugal pump, can be removed by a heat exchanger (copper coil) installed in the water collection tank.

Compressed air from a University source flows through the air regulator and filter and then flows through the air measuring station, where the air flow rate, temperature and pressure are measured. After that, the air flows to one of the mixers, in which it is well mixed with water.

The mixture of air and water then flows to the visual section, which is made of cast acrylic. The distance from the mixer to the visual section is over 60 times the diameter of the pipes. The air–water flow pattern in a straight pipe can be observed in the visual section. The test sections are located after the visual section. After exiting from the test section, the air–water mixture flows into a separator tank, from which the air escapes to the ambient, and the water is then returned to the water collection tank. Therefore, the water line is a closed circulation loop. In addition, the air flow rate and water flow rate are monitored by valves mounted in the flow loop. The check valves are used to guarantee flow in one direction. The air and water flow rates are measured by Fisher & Porter rotameter-type flow meters for a wide range of values.

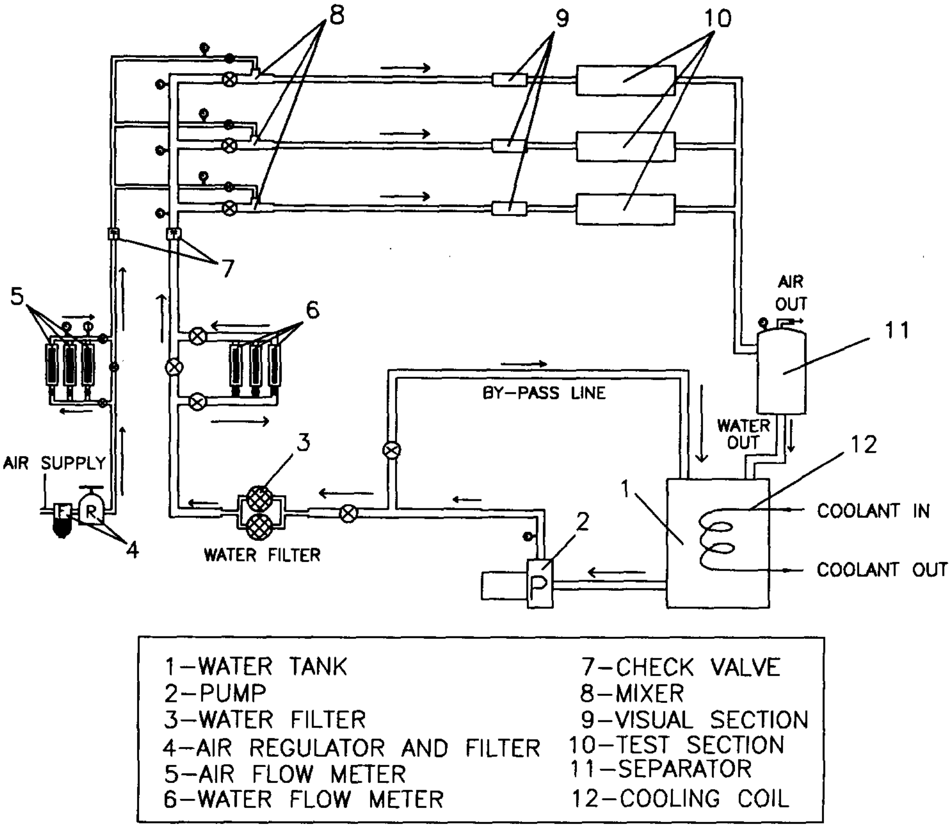


Figure 1. Schematic representation of the experimental system.

The mixers are designed like tee sections, as shown in figure 2. The air flows from a tee-leg through its own curved tube with small holes distributed throughout. The air is then discharged in the water flow and mixed to form a homogeneous mixture of air and water. The design of the air–water separator is illustrated in figure 3. The air–water flow exiting from the test sections flows into the separator tank from the top and is separated by centrifugal force through the nozzle. The water then flows down and drains from the bottom to the water collection tank and the air escapes to the ambient through the valve at the top of the separator.

The test section is shown in figure 4. The helicoidal pipe was made by wrapping a Tygon tube around a circular concrete form. The helical coil was then fixed and carefully tightened with clamps in order to avoid the deformation of the pipe. The entire test section was horizontally mounted on a frame to prohibit vibration. The advantages of this construction are two-fold. One, it was easy to observe the entire flow pattern in the transparent helical tube, and two, it was easy to change

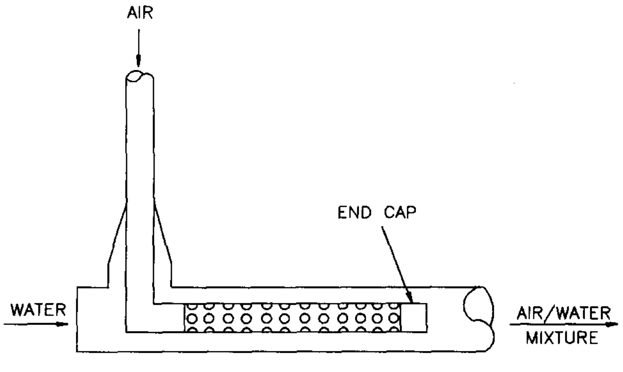


Figure 2. Air–water mixer.

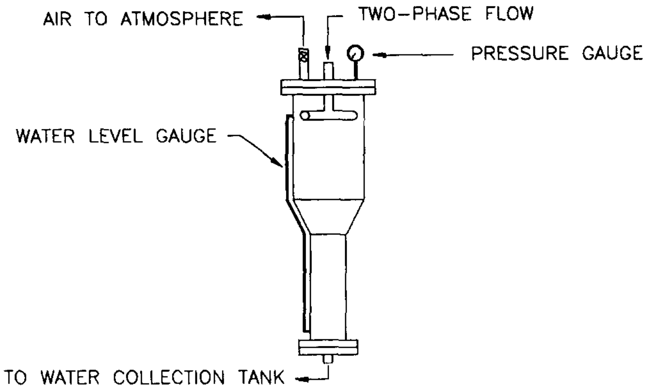


Figure 3. Air–water separator tank.

the helix (pitch) of the helical coils. Four different inside diameters of tubing (12.7, 19.05, 25.4 and 38.1 mm) and two different outside diameters of concrete forms (304.8 and 609.6 mm) were used to make the helicoidal pipes with different tube to coil diameter ratios. Pressure taps were located at the bottom of the horizontal helicoidal pipe, and are also shown in figure 4. The upstream pressure tap was mounted after one or two coil turns in order to reduce the effect of the upstream flow. The two pressure taps were adjusted to ensure that they were on the same level. The pressure difference was measured by a differential pressure transducer (wet/wet). Since water was always flowing near the bottom of the helicoidal pipe, the collection tube lines between the taps and the pressure transducer were full of water. Also, the pressure of the air–water mixture was measured at the inlet of the separator tank. Therefore, the absolute average pressure in the test section was calculated.

EXPERIMENTAL PROCEDURE

The experiments were conducted for air–water two-phase flow in four helicoidal pipes constructed of Tygon tubing with various diameters, $d = 12.7$, 19.1, 25.4 and 38.1 mm, which were wrapped around two concrete forms of different diameters. Also, the helix of each helicoidal pipe was changed, up to 20 degrees. The geometric configuration of the helicoidal pipes are given in table 1. A total of 32 helicoidal pipes was tested and the pressure drop data were taken. Furthermore, the superficial velocities of air and water ranged from 0.2–50.0 and 0.008–2.2 m/s, respectively.

The helicoidal pipes with diameters of 12.7, 25.4 and 38.1 mm were connected directly to the air–water two-phase flow loop when tested. The 19.1 mm diameter helicoidal pipe was connected to the 25.4 mm air–water flow loop with a transition tube. The helicoidal pipes were aligned and leveled during installation. Afterwards, the entire flow loop and test section were checked to ensure against leakage of air or water.

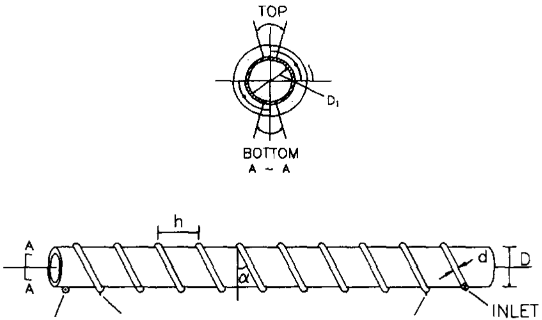
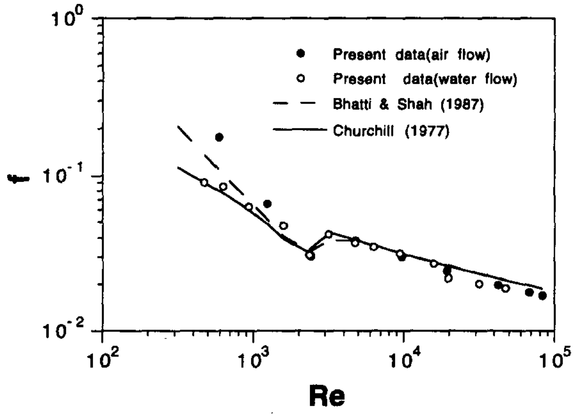


Figure 4. Helicoidal pipe configuration.

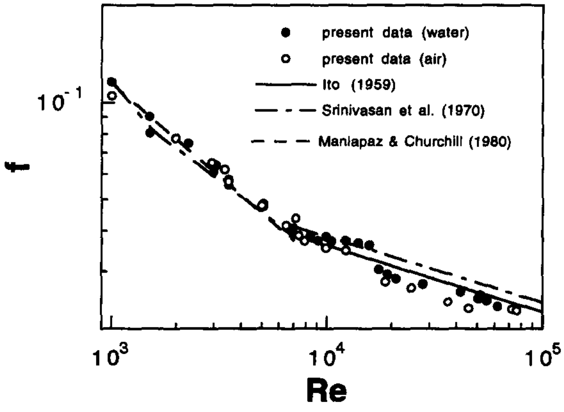
Table 1. Geometric configurations of the helicoidal pipe

No.	Pipe diameter (mm)	Coil diameter (mm)	Helix angle (degree)	Turns
1–4	12.7	330	1.0, 5, 10, 20	7, 7, 7, 5
5–8	19.1	340	1.5, 5, 10, 20	14, 14, 14, 6
9–12	25.4	350	2.0, 5, 10, 20	8, 8, 7, 6
13–16	38.1	360	2.6, 5, 10, 20	8, 8, 7, 6
17–20	12.7	640	0.5, 5, 10, 20	5, 5, 5, 4
21–24	19.1	650	0.8, 5, 10, 20	6, 6, 6, 5
25–28	25.4	660	1.0, 5, 10, 20	11, 8, 7, 4
29–32	38.1	670	1.4, 5, 10, 20	7, 4, 7, 4

To verify the experimental system, a series of experiments was conducted on single-phase flow (air and water) in a straight pipe, a helicoidal pipe (25.4 mm diameter, $\alpha = 10°$) and on air–water two-phase flow in a straight pipe. The friction factor for the single-phase flow versus the Reynolds number is given in figure 5, and the pressure drop multipliers versus the Lockhart–Martinelli parameters are given in figure 6. In these figures, the symbols represent the present experimental data, and the lines represent the correlations cited from the literature for single-phase flow or two-phase flow. It can be seen that very good agreement has been established between the experimental data and the predictions for either single-phase flow or two-phase flow. After that, the experiments on air–water two-phase flow in helicoidal pipes are conducted and the results are given in the following section.



(a) Straight pipe



(b) Helicoidal pipe

Figure 5. Comparison of the friction factor for single-phase flow.

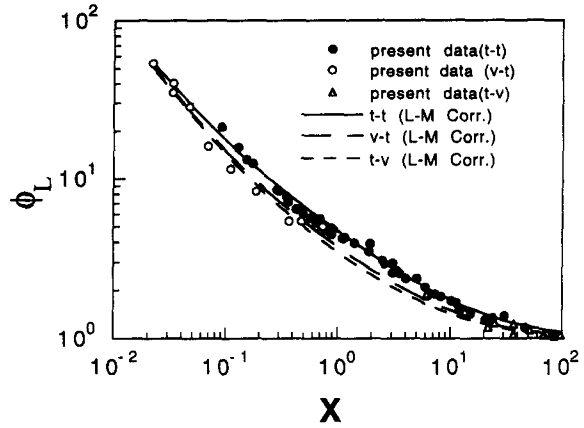


Figure 6. Comparison of the frictional pressure drop multiplier, ϕ_L, for two-phase flow in a straight pipe.

RESULTS AND DISCUSSION

Theory

Basic assumptions were made in the data reduction for the two-phase flow in the helicoidal pipe: the liquid and gas phase pressure drops were equal; and the two-phase pressure drops were also equal. Owing to no phase change, the accelerative effects were ignored. On the other hand, the pressure drop due to gravity (or the static head pressure gradient) was zero because the helicoidal pipe was horizontally oriented. Any interaction between the two-phases was neglected. Therefore, the general equation for the pressure drop gradient in the two-phase flow is:

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

which is simplified into:

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

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.

Since the Lockhart–Martinelli approach is commonly used for analysis of pressure drop in a straight pipe, as well as a vertical helicoidal pipe, analysis of the frictional pressure drop in the horizontal helicoidal pipe was attempted in the present research. According to the Lockhart–Martinelli method, the frictional pressure gradient in the two-phase flow, $(dp/dz)_{TPf}$, is related to that of gas or liquid phase flowing in helicoidal pipes. The results are presented in terms of pressure drop multipliers, ϕ_G and ϕ_L, versus the Lockhart–Martinelli parameter, X, which are defined as:

$$\phi_G^2 = \frac{(dp/dz)_{TPf}}{(dp/dz)_G} \quad [3]$$

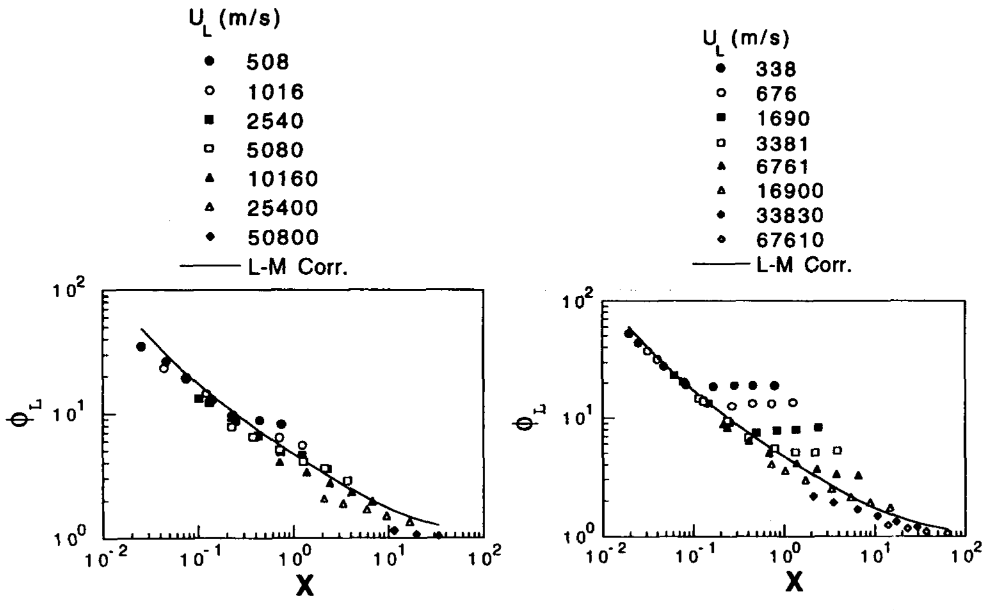
$$\phi_L^2 = \frac{(dp/dz)_{TPf}}{(dp/dz)_L} \quad [4]$$

and

$$X^2 = \frac{(dp/dz)_L}{(dp/dz)_G} \quad [5]$$

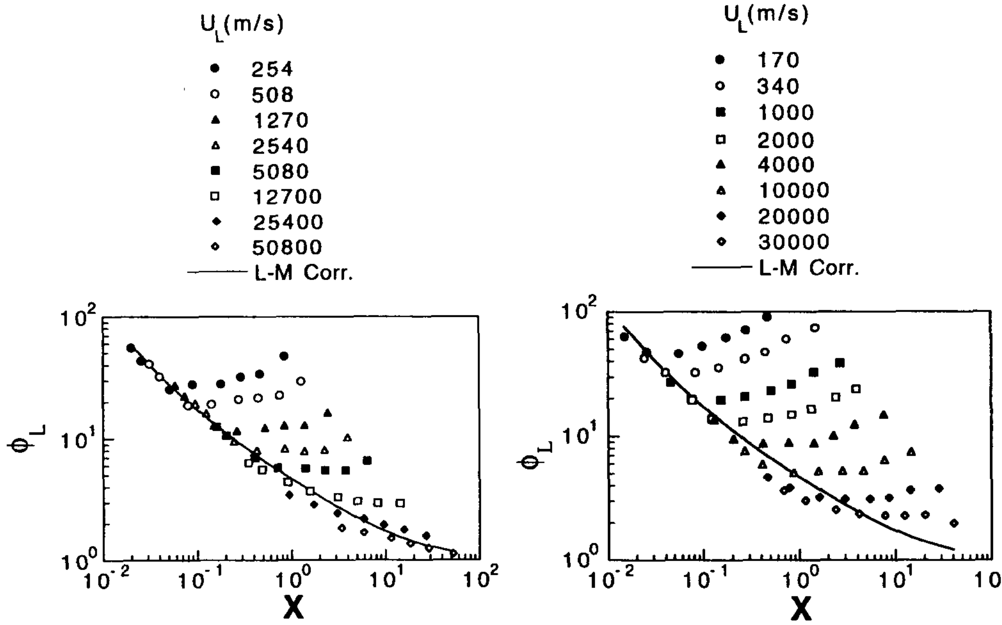
The single-phase pressure drop used in [3] and [4] or [5] can be calculated from the following equations:

$$\left(\frac{dp}{dz}\right)_G = 2f_G\rho_G U_G^2/d \quad [6]$$



(a) d=12.7mm, α=10°

(b) d=19.1mm, α=5°



(c) d=25.4mm, α=20°

(d) d=38.1mm, α=2.56°

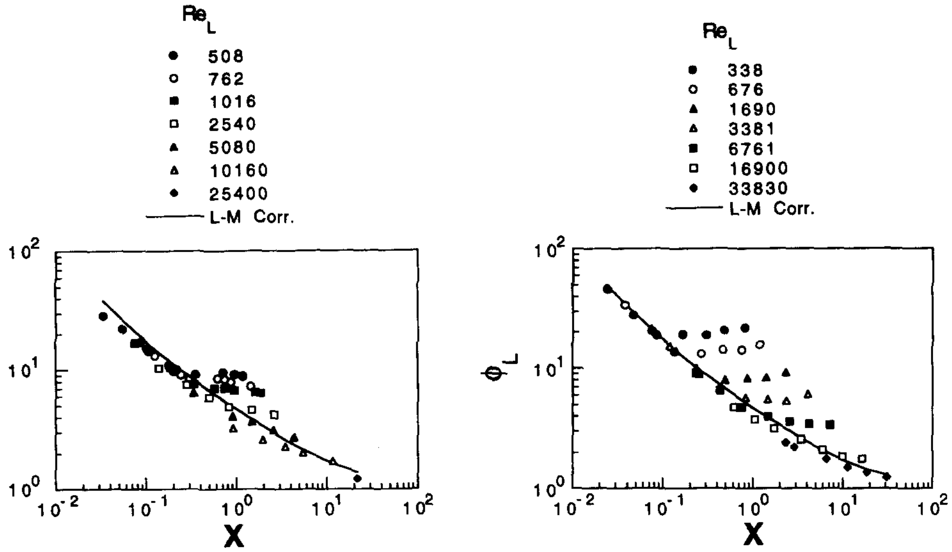
Figure 7. ϕ_L vs X for a small coil.

$$\left(\frac{\mathrm{d}p}{\mathrm{d}z}\right)_L = 2f_L \rho_L U_L^2/d \qquad [7]$$

and $(\mathrm{d}p/\mathrm{d}z)_{\mathrm{TPf}}$ is obtained from the measured pressure drop data,

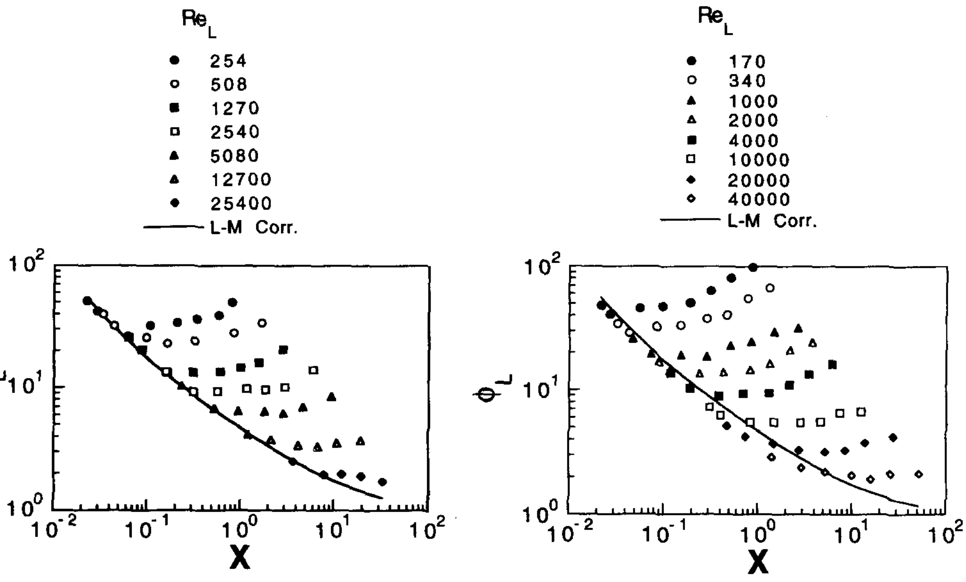
$$\left(\frac{\mathrm{d}p}{\mathrm{d}z}\right)_{\mathrm{TPf}} = \frac{\Delta P}{\pi D n/\cos\alpha} \qquad [8]$$

where D, n and α are coil diameter, coils turns and helix angle, respectively. ΔP measures the pressure drop between the two pressure taps. Friction factors, f_G or f_L, for the single-phase flow



(a) d=12.7 mm, α=5°

(b) d=19.1 mm, α=0.5°



(c) d=25.4 mm, α=10°

(d) d=38.1 mm, α=20°

Figure 8. ϕ_L vs X for a large coil.

in helicoidal pipes is calculated from the following equations for laminar flow (Manlapaz & Churchill 1980):

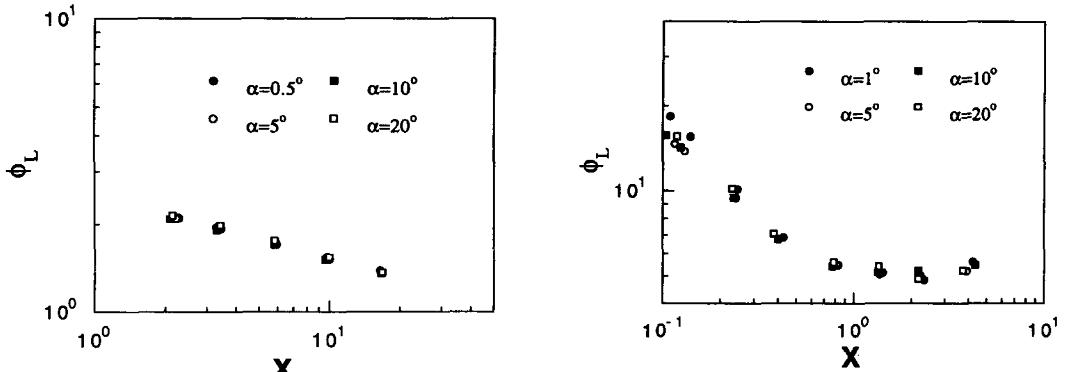
$$\frac{f}{f_s}=\left[\left(1.0-\frac{0.18}{[1+(35/\mathrm{De})^2]^{0.5}}\right)^m+\left(1.0+\frac{d/D}{3}\right)^2\left(\frac{\mathrm{De}}{88.33}\right)\right]^{2.5} \qquad [9]$$

where $m = 2$ for $\mathrm{De} < 20$, $m = 1$ for $20 < \mathrm{De} < 40$ and $m = 0$ for $\mathrm{De} > 40$ and $f_s = 16/\mathrm{Re}$, and for turbulent flow (Ito 1959):

$$f\left(\frac{D}{d}\right)^{0.5}=0.00725+0.076\left[\mathrm{Re}\left(\frac{D}{d}\right)^{-2}\right]^{-0.25} \quad \text{for } 0.034<\mathrm{Re}\left(\frac{D}{d}\right)^{-2}<300. \qquad [10]$$

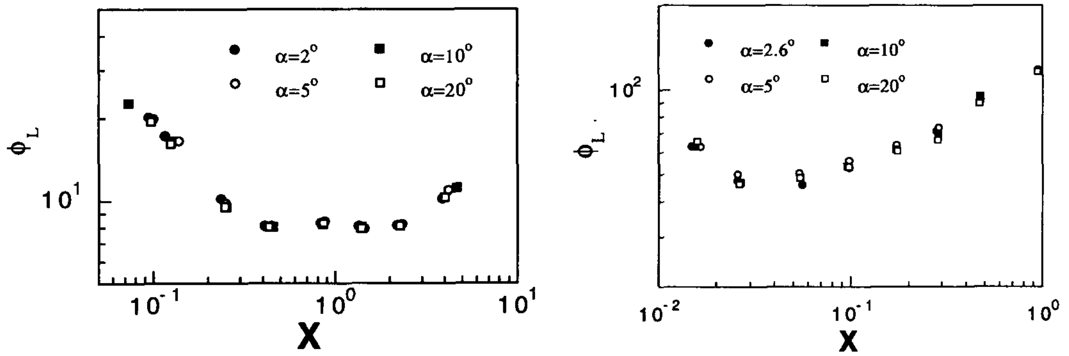
The Reynolds number and Dean number in [9] and [10] are defined as:

$$\mathrm{Re}=\frac{\rho U d}{\mu} \quad \text{and} \quad \mathrm{De}=\mathrm{Re}\left(\frac{d}{D}\right)^{1/2} \qquad [11]$$



(a) d=12.7 mm, Re_L=25400

(b) d=19.1 mm, Re_L=3381



(c) d=25.4 mm, Re_L=2540

(d) d=38.1 mm, Re_L=170

Figure 9. Effect of the helix angle on pressure drop multiplier, ϕ_L, for a small coil.

In addition, the transitional Reynolds number is obtained by

$$\mathrm{Re}_{\mathrm{tr}} = 2100\left(1 + 12\sqrt{\frac{d}{D}}\right) \qquad [12]$$

Overview

The experiments have been performed in order to explore the effects of the pipe diameter, coil diameter, helix angle and flow rates of air and water on two-phase flow in the horizontal helicoidal pipe. Numerous amounts of data were taken from the pressure drop measurements. Therefore, only the pressure drop multiplier, ϕ_L, and the Lockhart–Martinelli parameter, X, are used in the following figures. The ϕ_L variations versus X for small coils with different pipe diameters and helix angles are shown in figure 7, while the variations of ϕ_L versus X for large coils are displayed in figure 8. The Reynolds number calculated from the superficial velocity of water flow, Re_L, is used as parameters in those figures. It can be seen that ϕ_L strongly depends on the flow rate. For purposes of comparison, the Lockhart–Martinelli correlation for a straight pipe is represented by a solid line in the graphs. It should be pointed out that the direction for the increase in the superficial air velocity is the same as the direction of the decrease in X. It can be observed from figures 7 and 8 that the behaviors of ϕ_L versus X are the same for all the tested helicoidal pipes having different helix angles, coil diameters and pipe diameters. When the flow rate (superficial velocity) (either air or water) is higher, the data are close to the solid line; otherwise, the pressure drop multiplier varies as the flow rate changes. This flow rate effect was also found in vertical helicoidal pipes (Banerjee *et al.* 1969), but it was not so striking. For the horizontal helicoidal pipe, a water column forms in the upward side of the coil, when the water flow rate is lower, where its behavior is unstable, pulsed or intermittent. The water column is periodically broken by air flow, and then reforms. When the flow rate is higher, the air–water flow patterns are represented by

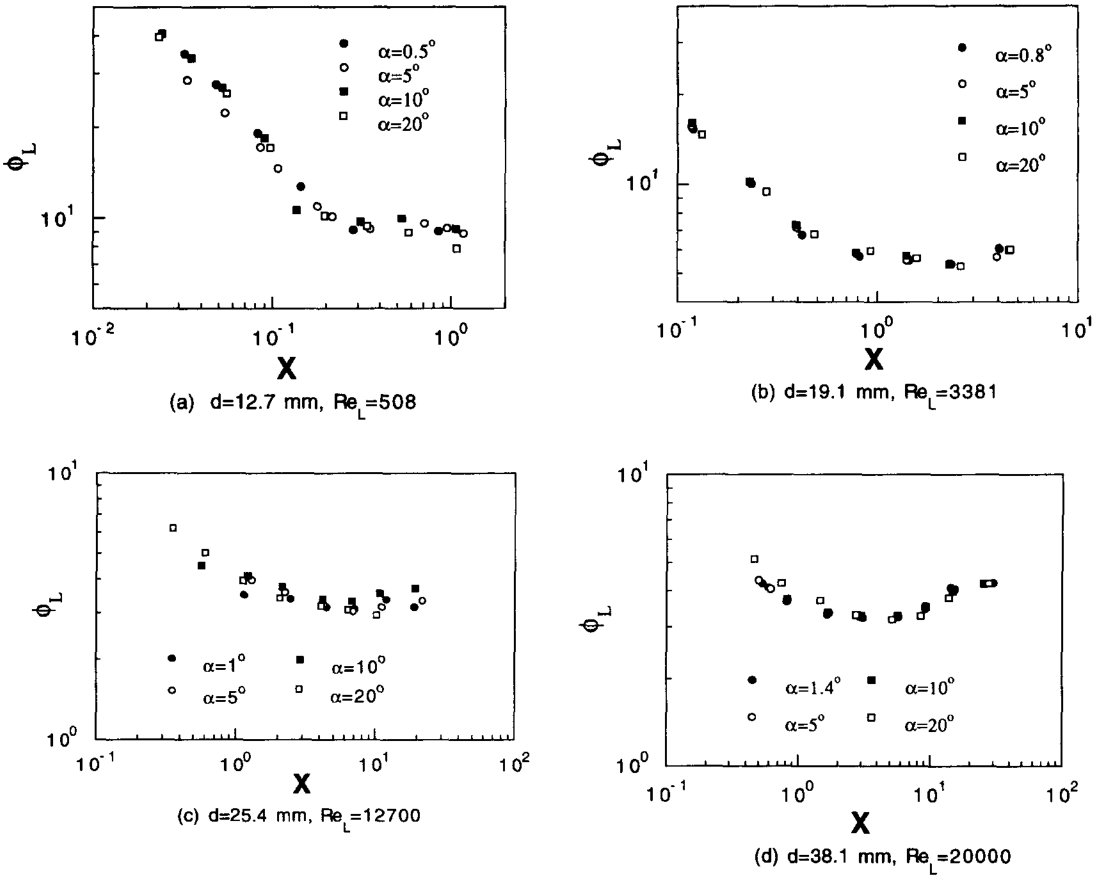


Figure 10. Effect of the helix angle on pressure drop multiplier, ϕ_L, for a large coil.

steady, annular flow, separated flow or annular–separated flow. The pressure drop data appear close to the solid line in figures 7 and 8.

Effect of the helix angle

In order to directly observe the effect of the helix angle on the pressure drop, figures 9 and 10 are plotted for helicoidal pipes with large and small coils. The plots in these two figures are arranged to show the effects of the helix angle on ϕ_L versus X with different values of Re_L for different pipes. The specific parameters of the pipe diameter and Re_L are given in the plot correspondingly. It can be observed in each graph that the pressure drop multiplier data are close to each other when the helicoidal pipe has a different helix angle. It follows that the helix angle has almost no effect on the pressure drop in two-phase flow in helicoidal pipes. This may be explained by the fact that the torsion force due to the helix angle is not comparable to the turbulence of two-phase flow, which is the major source generating the pressure drop in two-phase flow. Therefore, the effect of the helix angle in the two-phase flow pressure drop can be ignored.

Effect of the coil diameter

The effect of the coil diameter on ϕ_L is given in figure 11. Each plot in figure 11 represents results for a specific diameter of the helicoidal pipe with a helix angle equal to 10°. The pipe diameter and d/D are specified on each plot. Also, Re_L is used as a parameter. It can be observed that the coil diameter has a certain effect on the pressure drop multiplier, ϕ_L. However, the effect of the coil diameter diminishes as the Re_L increases. It seems that the pressure drop, ϕ_L, is independent of the coil diameter in the helicoidal pipe with a large diameter ($d = 38.1$ mm). As the flow rate decreases, the effect of the coil diameter on ϕ_L is notable.

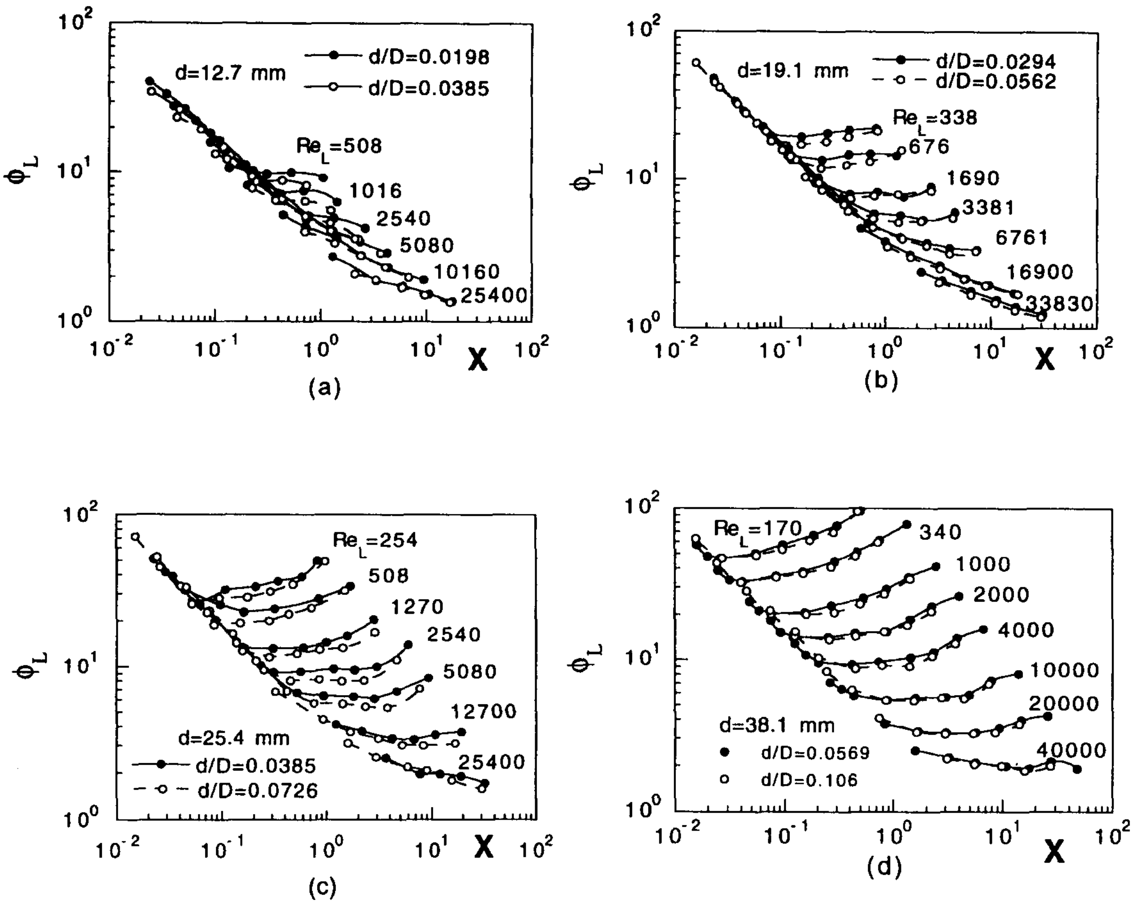
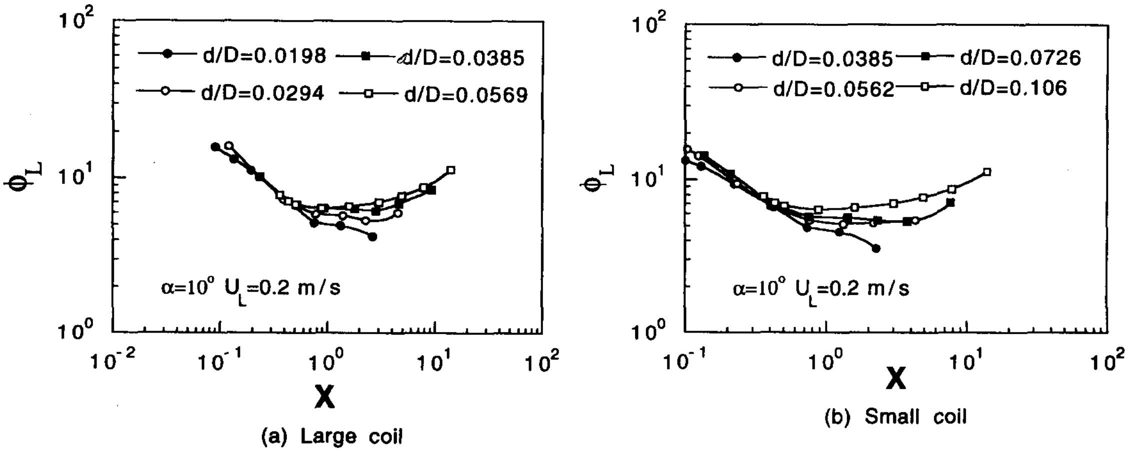


Figure 11. Effect of the coil diameter on pressure drop multiplier, ϕ_L.

Effect of the pipe diameter

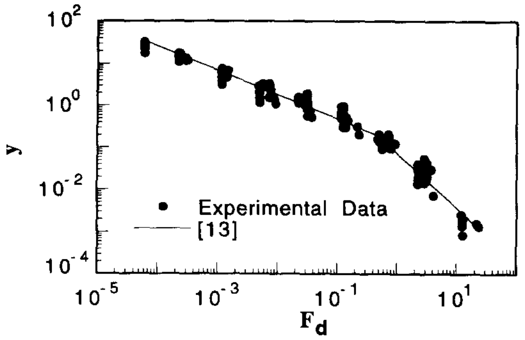
The effect of the pipe diameter on the pressure drop multiplier, ϕ_L, is shown in figure 12. The same parameters of the helix angle and superficial water velocity are applied in figure 12(a) for large coils and in figure 12(b) for small coils. The helix angle is 10° and the superficial water velocity is 0.2 m/s. The effects of the pipe diameter on the pressure drop were observed, and the data scattered to a certain extent, especially in the range of a larger value of X.



(a) Large coil

(b) Small coil

Figure 12. Effect of the tube diameter on pressure drop multiplier, ϕ_L.



$y = \phi_L(x^2+12x+1)^{-1/2} - x^{-1}$

Figure 13. Prediction vs experimental data.

The correlation

Unlike the two-phase flow in straight pipes, the frictional pressure drop depends on the flow rate in helicoidal pipes. The L–M correlation is not valid in the prediction except in the high flow rates. Based on experimental observation of the air–water two-phase flow in horizontal helicoidal pipes, the deviation of experimental data from the L–M prediction is caused basically because of the water column accumulation in the helicoidal pipe. Therefore, the Froude number, defined as U_L^2/gd, is introduced in the correlation. Another dimensionless parameter is d/D, which represents the effect of the configuration of the horizontal helicoidal pipes. A new correlation has been worked out as follows:

$$\phi_L = \left[1 + \frac{X}{C[F_d]^n}\right]\left(1 + \frac{12}{X} + \frac{1}{X^2}\right)^{1/2} \qquad [13]$$

where

$$F_d = \mathrm{Fr}\left(\frac{d}{D}\right)^{0.1} = \frac{U_L^2}{gd}\left(\frac{d}{D}\right)^{0.1} \qquad [14]$$

when $F_d \leqslant 0.3$, $C = 7.79$ and $n = 0.576$; when $F_d > 0.3$, $C = 13.56$ and $n = 1.3$.

The non-linear data regression method is used to obtain [13]. The determination of the values of C and n is based on the idea that the deviation between experimental data and prediction has to be minimized. The maximum deviation between the prediction by [13] and the experimental data is less than ±32% in the present experimental range. On the other hand, the variation of $\{\phi_L(X^2+12X+1)^{-1/2} - X^{-1}\}$ with F_d is displayed in figure 13. It shows that there is a significant change at F_d equal to 0.3.

Experimental uncertainty

Two quantities of the direct measurements are the flow rate and the pressure drop. Both the air and water flow rates were measured by three Fisher & Porter rotameter-type flow meters with an accuracy of ±2%. The pressure drop was measured by two Rosemount pressure transducers with an accuracy of ±2%. The accuracy of other quantities, such as length and properties, was estimated as 1 and 0.25%, respectively. Analyses of the uncertainties of ϕ_L or ϕ_G and X were conducted throughout the experiments. It was estimated that the uncertainties of ϕ_L or ϕ_G were 5.14% and the uncertainty of X was 9.2%.

CONCLUSION

The experiments on air–water two-phase flow in helicoidal pipes have been conducted for superficial air velocity in the range of $U_G = 0.2$–50 m/s and superficial water velocity in the range of $U_L = 0.008$–2.2 m/s. Thirty-two helicoidal pipes were tested to explore the effects of helix angles, pipe diameters and coil diameters on the pressure drop. The following conclusions have been drawn from the present study:

1. The frictional pressure drop multiplier, ϕ_L or ϕ_G, is not only a function of the Lockhart–Martinelli parameter, X, but also depends on the flow rate of the water and air.
2. It was found that the helix angle has almost no effect on the frictional pressure drop multiplier. However, the pipe and coil diameters have certain effects on the frictional pressure drop multiplier, but the effect diminishes as the water flow rate increases.
3. The frictional pressure drop correlations of the two-phase flow are provided with [13] in the present experimental range.

REFERENCES

Akagawa, K., Sakaguchi, T. & Ueda, M. 1971 Study on gas–liquid two-phase flow in helically coiled tubes. *Bull. JSME* **14,** 564–571.

Banerjee, S., Rhodes, E. & Scott, D. S. 1969 Studies on concurrent gas–liquid flow in helically coiled tubes, I—flow patterns, pressure drop and holdup. *Can. J. Chem. Engng* **47,** 445–453.

Berger, S. A. & Talbot, L. 1983 Flow in curved pipes. *A. Rev. Fluid. Mech.* **15,** 461–512.

Boyce, B. E., Collier, J. G. & Levy, J. 1969 Hold-up and pressure drop measurement in the two-phase flow of air-water mixing tubes in helical coils. *Proc. of Int. Symp. on Research in Concurrent Gas and Liquid Flow* (Edited by Rhodes, E. & Scott, D. S.), pp. 203–231. Plenum Press, New York.

Chen, S. J. & Zhou, F. D. 1981 An investigation of flow pattern and frictional pressure drop characteristics of air water two-phase flow in helical coils. *Proceedings of 4th Miami International Conference on Alternate Energy Sources*, pp. 120–129.

Hart, J., Ellenberger, J. & Hamersma, P. J. 1988 Single- and two-phase flow through helically coiled tubes. *Chem. Engng Sci.* **43,** 775–783.

Ito, H. 1959 Friction factors for turbulent flow in curved pipes. *J. Basic Engng* **81,** 123–134.

Kasturi, G. & Stepanek, J. B. 1972a Two-phase flow—I. Pressure drop and void fraction measurement in concurrent gas liquid flow in a coil. *Chem. Engng Sci.* **27,** 1871–1880.

Kasturi, G. & Stepanek, J. B. 1972b Two-phase flow—II. Parameters for void fraction and pressure drop correlations. *Chem. Engng Sci.* **27,** 1881–1891.

Lockhart, R. W. & Martinelli, R. C. 1949 Proposed correlation of data for isothermal two-phase, two-component flow in pipes. *Chem. Engng Prog.* **45,** 39–48.

Manlapaz, R. L. & Churchill, S. W. 1980 Fully developed laminar flow in a helically coiled tube of finite pitch. *Chem. Engng Commun.* **7,** 57–78.

Mujawar, B. A. & Rao, M. R. 1981 Gas non-newtonian liquid two-phase flow in helical coils. *Indust. Engng Chem. Process Des. Dev.* **20,** 391–397.

Owhadi, A., Bell, K. J. & Crain, B. 1968 Forced convection boiling inside helically-coiled tubes. *Int. J. Heat Mass Transfer* **11,** 1779–1793.

Rangacharyulu, K. & Davies, G. S. 1984 Pressure drop and holdup studies of air–liquid flow in helical coils. *Chem. Engng J.* **29,** 41–46.

Ripple, G. R., Eidt, C. M. & Jornan, H. B. 1966 Two-phase flow in a coiled tube. *I&EC* **5,** 32–39.

Saxena, A. K., Schumpe, A. & Nigam, K. D. P. 1980 Flow regimes, holdup, and pressure drop for two-phase flow in helical coils. *Can. J. Chem. Engng* **68,** 553–559.

Shah, R. K. & Joshi, S. D. 1987 Convective heat transfer in a curved duct. In *Handbook of Single-phase Convective Heat Transfer* (Edited by Kakac, S., Shah, R. K. & Aung). Wiley, New York.