An experimental study of single-phase and two-phase flow pressure drop in annular helicoidal pipes

R. C. Xin, A. Awwad, Z. F. Dong and M. A. Ebadian
Florida International University, Hemispheric Center for Environmental Technology, Miami, Florida, USA

In this study, experimental investigations were conducted for single-phase and air/water two-phase flow in annular helicoidal pipes with vertical and horizontal orientations. Three test sections were investigated. The outer diameters of the inner tube were 12.7 mm, 9.525 mm, and 6.35 mm, and the inner diameters of the outer tube were 21.18 mm, 15.748 mm, and 10.21 mm, respectively. The experiments were performed for superficial water Reynolds numbers in the range of 210 to 23,000 and superficial air Reynolds numbers in the range of 30 to 30,000. The effects of coil geometry and the flow rates of air and water on single-phase and two-phase flow pressure drop were experimentally investigated for annular helicoidal pipes. The data were correlated as the relationship of the pressure drop multipliers versus Lockhart–Martinelli parameter for the two-phase flow. The average void fraction was also measured in the experiments by means of the quick acting valve method. Unlike two-phase flow in straight pipe, the pressure drop multipliers of two-phase flow in annular helicoidal pipes have been found to be dependent on the flow rate in addition to the Lockhart–Martinelli parameter for the annular helicoidal pipe with large diameter. Thus, the Lockhart–Martinelli correlation is not valid in the prediction. Correlations for two-phase flow in horizontal and vertical annular helicoidal pipes have been established for both single-phase and two-phase flow based on the present experimental data. © 1997 by Elsevier Science Inc.

Keywords: two-phase flow; single-phase flow; pressure drop; void fraction; annular helicoidal pipe

Introduction

Many investigations have been conducted regarding fluid flow in curved and helicoidal pipes with circular cross sections. Much of the work on single-phase flow has been summarized by Berger and Talbot (1983) and Shah and Joshi (1987). Two-phase flow in helicoidal pipes has been studied by many investigators, including Banerjee et al. (1969), Rippel et al. (1966), Boyce et al. (1969), Awwad et al. (1995), and Xin et al. (1996). Coiled tube-in-tube heat exchangers are widely used in nuclear power engineering, chemical engineering, and HVAC systems because of their compactness and effectiveness. However, fluid flow in annular helicoidal pipes has rarely been investigated for both single-phase and two-phase flows.

Numerical results indicate that the flow in a curved annulus differs significantly from that in a curved circular tube because of the presence of the inner-wall boundary (Karahalios 1990). The differences include the main flow and secondary flow patterns and, hence, the friction factor and heat transfer coefficients. For curved annular tubes, there are two pairs of vortices of the secondary flow in the cross section. For the large pipe diameter ratio, the two vortices near the inner wall can be very small, but for the small diameter ratio, those two vortices near the inner wall can be as large as the two near the outer wall (Choi and Park 1994). Garimella et al. (1988) investigated the forced-convection heat transfer in coiled annular ducts experimentally. Two coils were tested by flowing hot and cold water through the shell side and tube side, respectively. Some Nusselt number correlations were suggested for laminar and transition flow regimes. Developing laminar flow in curved annuli was studied numerically by Choi and Park (1992). Evolution of the secondary flow and the effect of radius ratio on the flow development were also discussed in their work. Some analytical and numerical studies on mixed convection flow in curved annular ducts can be found in Karahalios (1990) and Park and Choi (1993).

Few studies have been done for two-phase flow characteristics in curved and helicoidal pipes with annular cross sections. A number of experimental studies on two-phase flow in the circular helicoidal pipes are cited and discussed for comparison. The results reported by authors such as Rippel et al. (1966) and Banerjee et al. (1969) indicate that most of the pressure drop data for two-phase flow in vertical helicoidal pipes can be predicted satisfactorily by the Lockhart–Martinelli correlation, with the specific definition of the Lockhart–Martinelli parameter based on the single-phase flow friction pressure drop in helicoidal pipe. In addition to the Lockhart–Martinelli parameter,

Address reprint requests to Dr. M. A. Ebadian, Hemispheric Center for Environmental Technology, Florida International University, Miami, FL 33199, USA.

Received 17 December 1996; accepted 5 March 1997

Int. J. Heat and Fluid Flow 18: 482–488, 1997

655 Avenue of the Americas, New York, NY 10010

0142-727X/97/$17.00
PII S0142-727X(97)00033-7

some effects of liquid velocity on pressure drop have also been observed (Boyce et al. 1969; Banerjee et al. 1969). Furthermore, Xin et al. (1996) and Awwad et al. (1995) have obtained extensive data on the pressure drop of two-phase flow in vertical and horizontal helicoidal pipes, respectively. The effect of liquid flow rate on pressure drop multipliers was also discussed in detail in these two papers, and correlations were proposed for both vertical and horizontal helicoidal pipes.

The literature review indicates that previous studies have addressed single- and two-phase flow in circular helicoidal pipes. The flow characteristics of single-phase in annular curved and helicoidal pipes have been studied numerically (Karahalios 1990), and the heat transfer was studied experimentally (Garimella et al. 1988). To our knowledge, two-phase flow in annular curved and helicoidal pipes has not been studied. Therefore, in this paper, the pressure drop of single-phase flow and two-phase flow in annular helicoidal pipes is investigated experimentally, and correlations for pressure drop calculation are provided for design purposes. The void fraction results for the two-phase flow in annular helicoidal pipe are also reported.

Experimental apparatus

The experiments of single- and two-phase flow of air and water in annular helicoidal pipes were conducted in the Heat Transfer Laboratory of the Hemispheric Center for Environmental Technology (HCET) at Florida International University (FIU). The experimental system consisted of an air/water flow loop and a test section. A schematic representation of the experimental system is shown in Figure 1. A detailed description of the system can be found in Awwad et al. (1995).

Three test sections were used. A schematic drawing of the test sections is presented in Figure 2. The dimensions of these test sections are listed in Table 1. Both the inner and outer tubes were made of copper. Two pressure taps were positioned after the inlet elbow and before the outlet elbow for each test section. The pressure drop and the gauge pressure at the exit of the test section were measured by two diaphragm differential-pressure transducers with a measurement capacity of 3.45×10^5 Pa and 1.0133×10^5 Pa, respectively, and an accuracy of $\pm 2\%$. The signals from the pressure transducers and thermocouples were sent directly to a Hewlett–Packard data acquisition system. Thirty readings were taken during a 2-min period in the pressure drop measurement. Subsequently, an average value was obtained to reduce the effect of the pressure fluctuations. All measurements were taken and controlled by the computer-controlled data acquisition system. The void fraction was measured by the quick-shut valve method, as described in the study by Xin et al. (1996). The mass of water holdup in two-phase flow and the maximum mass of water the test section could hold were measured using a calibrated electronic scale.

Analysis and data reduction

During the experiments, pressure drop in single-phase flow in annular helicoidal pipes was measured first. The resulting data were used as the bases for the two-phase flow analysis. The pressure drop and void fraction in two-phase flow were subsequently measured for vertical and horizontal orientations of each test section.

The pressure drop data for single-phase flow were correlated as the relationship of the friction factor with the Dean number for laminar flow and Reynolds number for turbulent flow. The Dean number (De) and Reynolds number (Re) are defined as follows:

$$\mathrm{Re} = \frac{\rho u (d_o - d_i)}{\mu}, \qquad \mathrm{De} = \mathrm{Re}\left(\frac{d_o - d_i}{D}\right)^{1/2} \tag{1}$$

The friction factor for single phase flow is determined using:

$$f = \frac{(\Delta p/L)(d_o - d_i)}{\frac{1}{2}\rho u^2} \tag{2}$$

The total pressure gradient in two-phase flow $(\mathrm{d}p/\mathrm{d}z)_t$ can be expressed in three terms:

$$\left(\frac{\mathrm{d}p}{\mathrm{d}z}\right)_t = \left(\frac{\mathrm{d}p}{\mathrm{d}z}\right)_f + \left(\frac{\mathrm{d}p}{\mathrm{d}z}\right)_a + \left(\frac{\mathrm{d}p}{\mathrm{d}z}\right)_g \tag{3}$$

where $(\mathrm{d}p/\mathrm{d}z)_f$ is the friction pressure gradient, $(\mathrm{d}p/\mathrm{d}z)_a$ is the acceleration pressure gradient, and $(\mathrm{d}p/\mathrm{d}z)_g$ is the gravitational pressure gradient. Because of the absence of phase change, the second term can be neglected. For two-phase flow in vertical

Notation

b	coil pitch, m
d_i	outer diameter of inner tube, m, defined in Figure 1
d_o	inner diameter of outer tube, m, defined in Figure 1
$\mathrm{d}p/\mathrm{d}z$	pressure gradient, Pa/m
D	coil diamter, m, defined in Figure 1
De	Dean number
f	friction factor
Fr	Froude number
g	gravitational acceleration, m/s^2
L	pipe length, m
n	coil turns
Re	Reynolds number
u	superficial velocity, m/s
X	Lockhart–Martinelli parameter

Greek

α	void fraction
β	helix angle
ρ	density, kg/m^3
Δp	pressure difference, Pa
ϕ	pressure drop multiplier

Subscripts

a	acceleration
f	friction
g	gravity
G	gas
L	liquid
p	phase, L or G
t	two-phase flow total

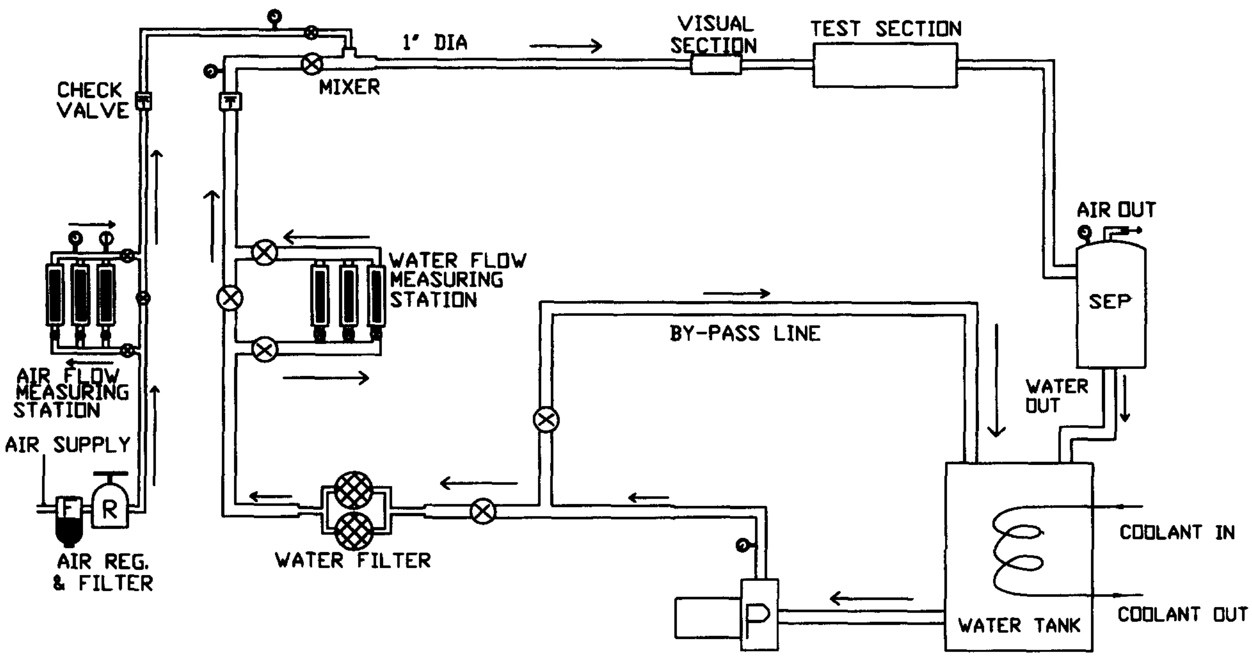


Figure 1 Schematic representation of the experimental system

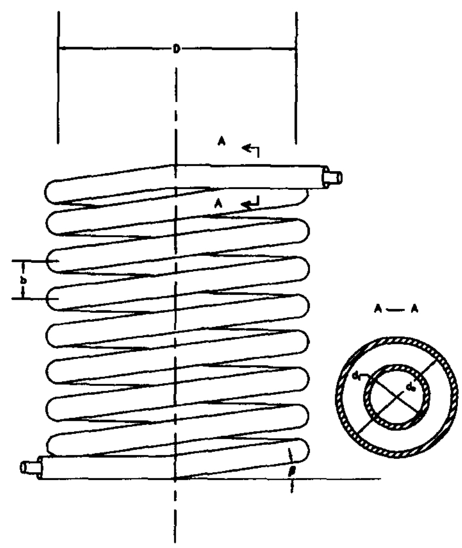


Figure 2 Geometry of the test section

Table 1 Dimensions of the test sections

Test section	d_i (mm)	d_o (mm)	b (mm)	D (mm)	n	$d_o - d_i$ (mm)
1	12.7	21.18	34.9	177.8	10	8.48
2	9.53	15.75	25.4	196.85	9	6.22
3	6.35	10.21	19.05	114.3	15	3.86

coils, the gravitational pressure gradient is determined from the void fraction data using the following equation:

$$\left(\frac{dp}{dz}\right)_g = \rho_L g(1-\alpha)\tan\beta \tag{4}$$

For horizontal coils, the net gravitational pressure gradient is zero for complete turns. Therefore, the friction pressure gradient can be determined from the total pressure gradient, which was measured in these experiments. It must be noted that the fluid properties, especially the gas properties, were determined using the average value of inlet and outlet pressures as a reference.

The friction pressure drop data are correlated as the pressure drop multipliers ϕ_G and ϕ_L versus Lockhart–Martinelli parameter X, which are defined as follows:

$$\phi_L^2 = \frac{(dp/dz)_f}{(dp/dz)_L}, \qquad \phi_G^2 = \frac{(dp/dz)_f}{(dp/dz)_G} \tag{5}$$

and

$$X^2 = \frac{(dp/dz)_L}{(dp/dz)_G} \tag{6}$$

The single-phase flow pressure gradients, $(dp/dz)_L$ and $(dp/dz)_G$, used in the above equations can be determined from the correlation obtained from the present single-phase flow experiments, which are discussed in the next section. For two-phase flow in annular helicoidal pipe, three forces affect the flow pattern and pressure drop: inertial force; liquid gravity; and centrifugal force. Inertial force enhances the mixing of the two phases. Because of the large density difference between the liquid and gas phases, liquid gravity and centrifugal force will separate the two phases if each of them acts alone on the flow. However, when the flow direction changes and/or the directions of the gravity and centrifugal force are opposite, the net effect can be the separating or mixing of the phases. The effects of these forces can be represented in terms of Fr, d/D, and $\tan\beta$. Therefore, the friction pressure drop multipliers can be correlated as a function of these three parameters as well as Lockhart–Martinelli parameter X. Because of the limitation of the experimental data, only the effect of Fr is correlated in this paper.

Results and discussion

Single-phase flow

All three test sections were examined for air and water flow. The results are presented in Figure 3. The prediction from the correlations proposed by Manlapaz and Churchill (1980) and Ito (1959) for circular curved pipe is also shown in Figure 3 for comparison. It seems that the friction factor results can be predicted with reasonable accuracy in the complete laminar and turbulent flow regions, but not in the transition region.

In Figure 3, it can be observed that the transition from laminar to turbulent flow is a gradual process that covers a Dean number range from approximately 800–4000. This range is larger than that found for circular helicoidal pipes (Xin et al. 1996). The critical Dean numbers predicted by Srinivasan's equation (Srinivasan et al. 1970) are 1661, 1139, and 1267 for the first, second, and third test sections, respectively. This phenomenon is worth discussing in more detail. In the case of circular helicoidal pipe, the transition from laminar to turbulent flow occurs at different Reynolds number and different locations in the outer region and inner region. Thus, the overall transition takes place in a range of Reynolds (or Dean) number instead of at a particular Reynolds number or in a very narrow range, as observed for straight pipe. Because two surfaces are involved in an annular helicoidal pipe, the transition of the flow near the inner tube seems to differ from the transition of the flow near the outer tube. However, this hypothesis must be verified further by experimental results.

As discussed above, no clear boundary exits between laminar flow and turbulent flow in annular helicoidal pipes. Therefore, using the least-squares fitting method of the Martinelli–Nelson scheme, all the experimental data are regressed to one correlation as follows:

$$f = 0.02985 + 75.89\left[0.5 - atan\left(\frac{\mathrm{De} - 39.88}{77.56}\right)\Big/\pi\right]\Bigg/\left(\frac{D}{d_o - d_i}\right)^{1.45} \qquad (7)$$

where De $= 35 - 20000$, $d_o/d_i = 1.61 - 1.67$, and $D/(d_o - d_i) = 21 - 32$. The comparison between the correlation and the experimental data is shown in Figure 4. The maximum deviation is approximately 15% in the present experimental region.

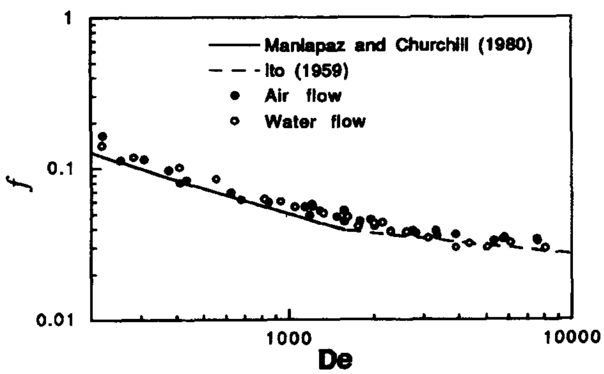
Two-phase flow in vertical coils

In Figure 5, the pressure drop multipliers for vertical coils are shown in terms of the Lockhart–Martinelli parameter. Also, the Lockhart–Martinelli correlation for two-phase flow in straight pipe with turbulent liquid and gas phases, as following, is depicted with a dash line in each figure for comparison.

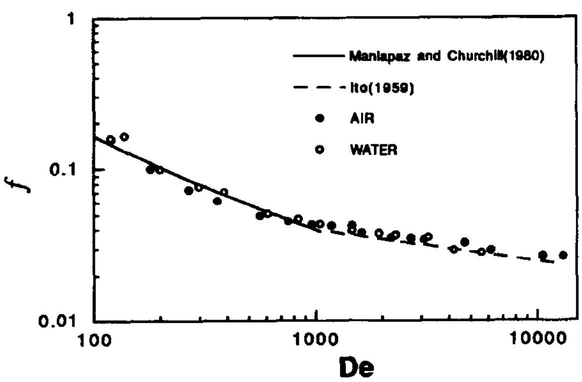
$$\phi_L^2 = 1 + \frac{20}{X} + \frac{1}{X^2} \qquad (8)$$

It can be observed that the pressure drop multipliers are lower than those predicted by the Lockhart–Martinelli correlation.

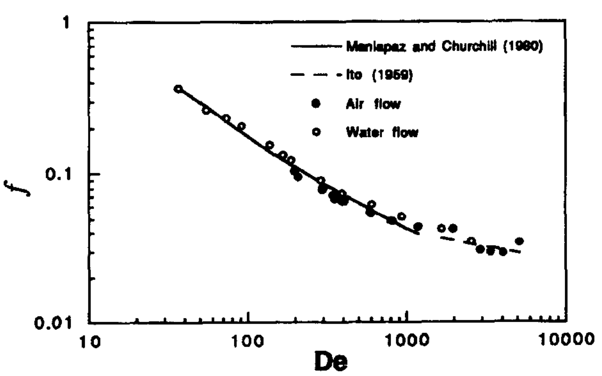
The void fraction results are presented in Figure 6. As with the results for two-phase flow in circular helicoidal pipes, the void fraction data for test sections 1 and 2 can be correlated by



(a) Test section 1



(b) Test section 2



(c) Test section 3

Figure 3 Friction factor of single-phase flow in annular helicoidal pipes

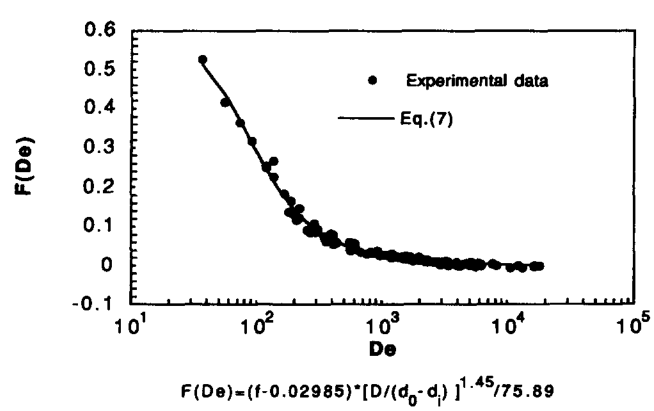
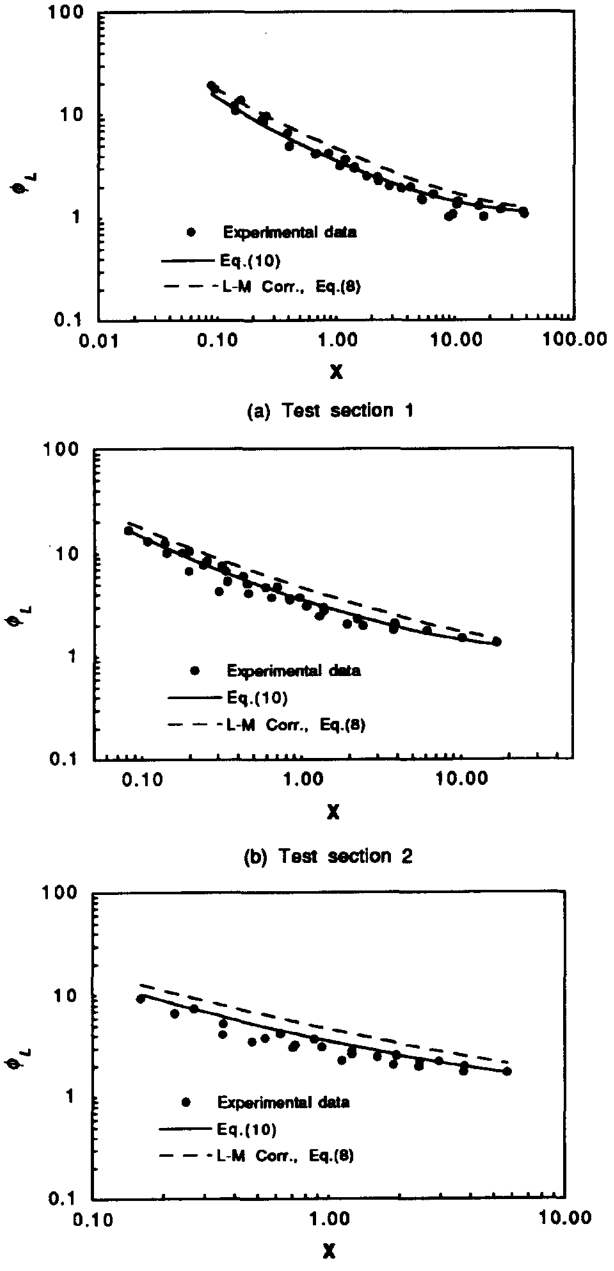


Figure 4 Comparison between experimental data and correlation of single-phase flow friction factor

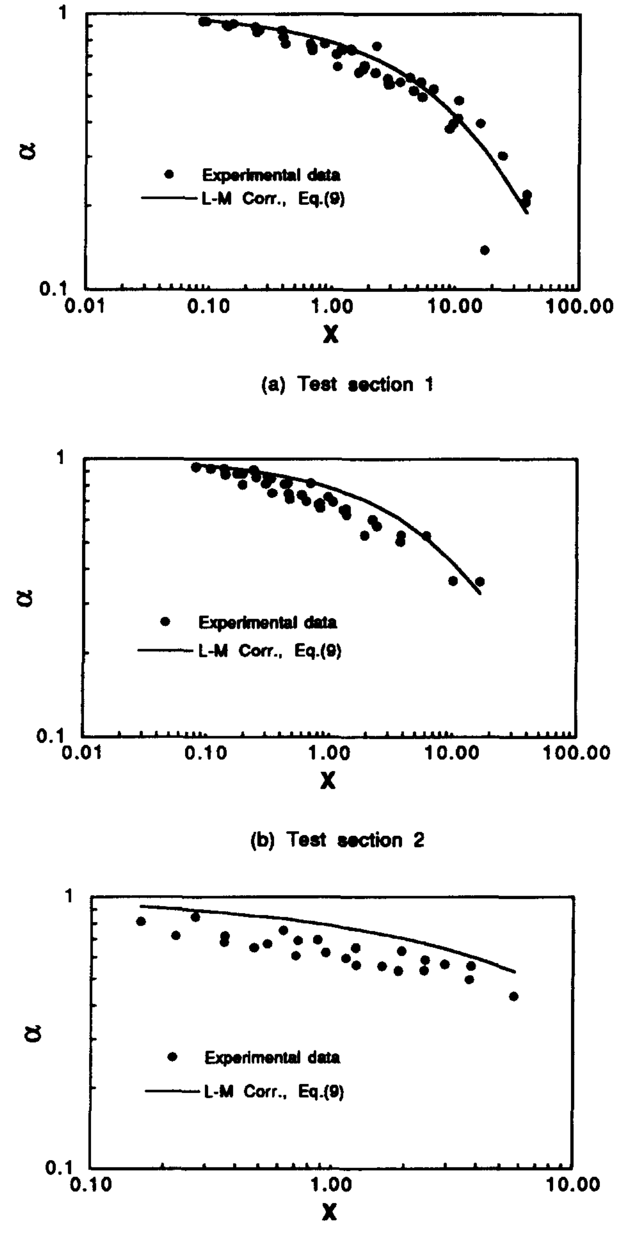


(a) Test section 1

(b) Test section 2

(c) Test section 3

Figure 5 Pressure drop multiplier versus Lockhart–Martinelli parameter for vertical coils



(a) Test section 1

(b) Test section 2

(c) Test section 3

Figure 6 Void fraction of vertical coils

Lockhart–Martinelli relation quite well:

$$\alpha = \frac{\phi_L - 1}{\phi_L} \tag{9}$$

It should be noted that the ϕ_L in Equation 9 is calculated using Equation 10, which is described in following section, instead of the Lockhart–Martinelli correlation for the pressure drop multipliers (Equation 8).

Two-phase flow in horizontal coils

The experimental data for pressure drop in horizontal coils are presented in Figure 7 as the pressure drop multipliers versus the Lockhart–Martinelli parameter. An examination of this figure reveals that the pressure drop multipliers are dependent not only on the Lockhart–Martinelli parameter but also on the liquid (or gas) flow rate for a large-pipe-diameter coil (test section 1). This phenomenon has also been observed for air/water two-phase flow in circular helicoidal pipe (Xin et al. 1996). Because the inner/outer tube diameter ratio, coil diameter, and pitch do not differ significantly, the differences in results from the different test sections can be attributed to the pipe hydraulic diameter $(d_o - d_i)$ effect. Physically, in the coils with small pipe diameter, the inertial force overwhelms the gravity, so the backflow of the liquid phase does not occur, which is thought to be the main reason of higher pressure drop in low Froude number region. To display this effect explicitly, Figure 8 is plotted at certain liquid superficial Reynolds numbers. As seen in this figure, as the hydraulic pipe diameter $(d_o - d_i)$ decreases, the pressure drop

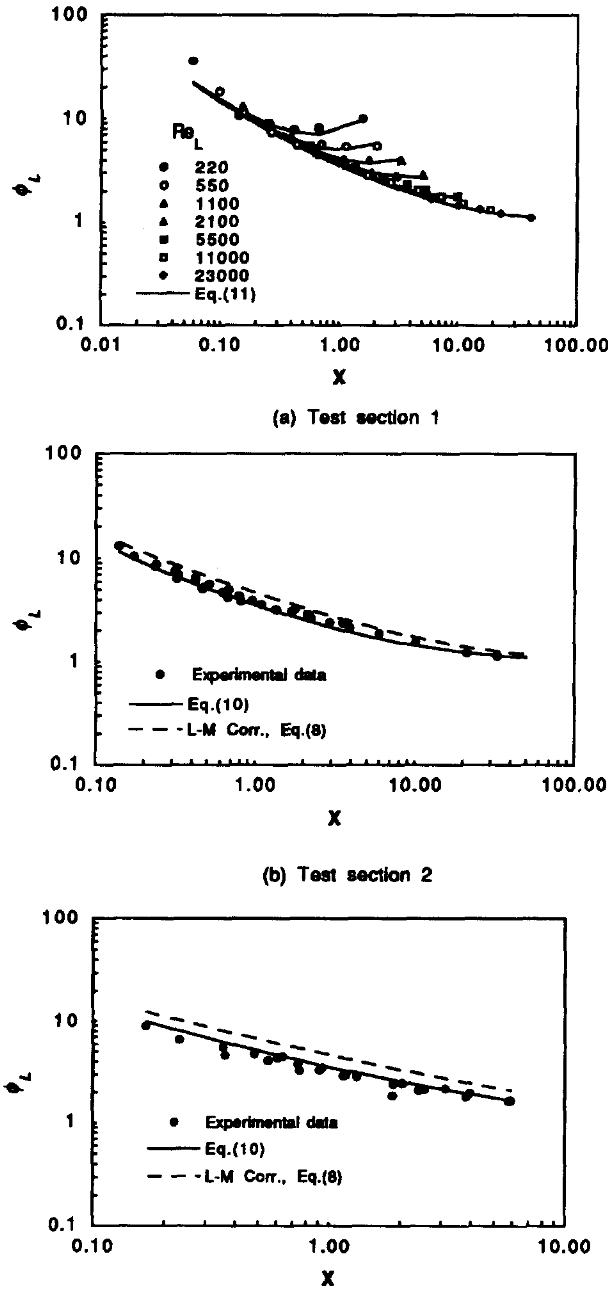


Figure 7 Pressure drop multiplier versus Lockhart–Martinelli parameter for horizontal coils

multiplier decreases and approaches a limit. On the other hand, the void fraction for the horizontal coils is described well by the Lockhart–Martinelli equation, as seen for test section 1 in Figure 9.

Correlations for two-phase flow

As discussed above, the liquid flow Reynolds number has little effect on the pressure drop multiplier ϕ_L for the vertical coils and test sections 2 and 3 in horizontal coils. As a result of a least-squares fitting, the experimental data suggest:

$$\phi_L^2 = 1 + \frac{10.646}{X} + \frac{1}{X^2} \tag{10}$$

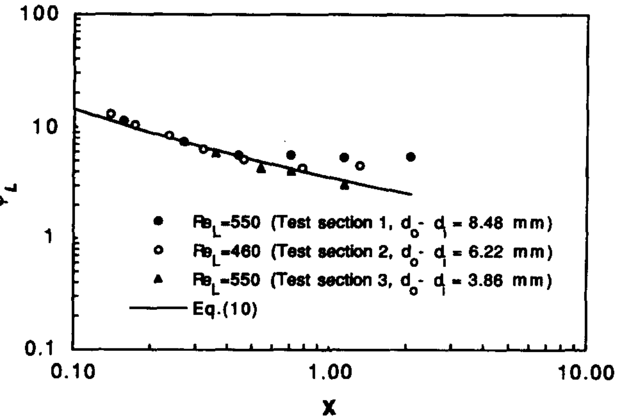


Figure 8 Effect of the pipe hydraulic diameter on pressure drop multiplier, ϕ_L

The above equation is valid in the range of $d_o/d_i = 1.61 - 1.67$ and $D/(d_o - d_i) = 21 - 32$. Compared with Lockhart–Martinelli correlation (Equation 8), the pressure drop multiplier ϕ_L of annular helicoidal pipe is lower than that of straight pipe under the same Lockhart–Martinelli parameter.

Predictions from this correlation are also shown in Figures 5 and 7 with the experimental data. For test section 1 in horizontal, the liquid flow Reynolds number effect is significant. Using the same correlating method (Xin et al. 1996), an effect factor of Froude number is introduced into Equation 11 and correlated by the least-squares method. The following pressure drop multiplier correlation as a function of Fr and X was obtained:

$$\phi_L = \left(1 + \frac{0.0435X^{1.5}}{F}\right)\left(1 + \frac{10.646}{X} + \frac{1}{X^2}\right)^{1/2} \tag{11}$$

where $F = \mathrm{Fr}^{0.9106} e^{0.0458(\ln \mathrm{Fr})^2}$, $d_o/d_i = 1.61 - 1.67$, $d_o = 21.18$ mm, and $D/(d_o - d_i) = 21$. Fr is the Froude number, defined as:

$$\mathrm{Fr} = \frac{u_L^2}{g(d_o - d_i)} \tag{12}$$

The experimental data and the correlation agree quite well, as can be observed in Figure 7a. When using Equations 10 and 11, the pressure gradient for the single phase flow in X and ϕ_L can be calculated from the following equation:

$$(\mathrm{d}p/\mathrm{d}z)_p = \frac{1}{2} f \frac{\rho_p u_p^2}{d_o - d_i} \qquad (p = L \text{ or } G) \tag{13}$$

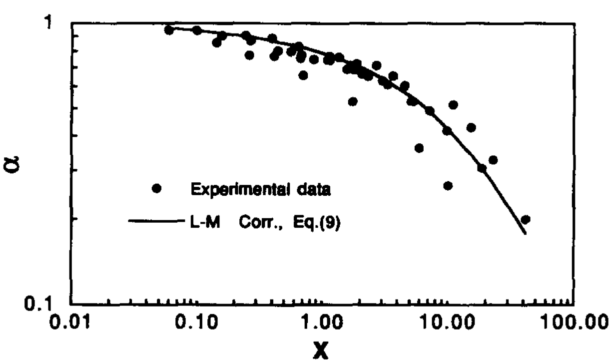


Figure 9 Void fraction of the horizontal coil (test section 1)

where f in Equation 13 can be calculated using Equation 7. Equations 10 and 11 were based on the experimental data of the parameter ranges of the present experiments. It is recommended to use them in the tested parameter ranges as stated.

Concluding remarks

Pressure drop experiments on single-phase and air/water two-phase flow in three annular helicoidal pipes have been conducted. For single-phase flow, the transition from laminar to turbulence covers a wider Reynolds number range. A correlation for the friction factor in laminar, transitional, and turbulent flow regimes has been proposed based on the present experimental data. For two-phase flow in horizontal annular helicoidal pipes with a large pipe diameter, 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 water or air. The flow rate effect decreases as the pipe diameter decreases. The frictional pressure drop correlations for the vertical and horizontal coils are provided in Equations 10 and 11. The void fractions for vertical and horizontal coils can be predicted fairly well by Lockhart–Martinelli relation if the pressure drop multiplier is calculated from the present correlation Equation 10.

Acknowledgment

The results presented in this paper were obtained in the course of research sponsored by the National Science Foundation.

References

Awwad, A., Xin, R. C., Dong, Z. F., Ebadian, M. A. and Soliman, H. M. 1995. Measurement and correlation of the pressure drop in air–water two-phase flow in horizontal helicoidal pipes. *Int. J. Multiphase Flow*, **21**, 607–619

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

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

Boyce, B. E., Collier, J. G. and Levy, J. 1969. Hold-up and pressure drop measurement in the two-phase flow of air–water mixing tubes in helical coils. In *Proceedings, International Symposium on Research in Concurrent Gas and Liquid Flow—1969*, E. Rhodes and D. S. Scott (eds.), Plenum Press, New York, 203–231

Choi, H. K. and Park, S. O. 1992. Laminar entrance flow in curved annular ducts. *Int. J. Heat Fluid Flow*, **13**, 41–49

Choi, H. K. and Park, S. O. 1994. Mixed-convection flow in curved annular ducts. *Int. J. Heat Mass Transfer*, **37**, 2761–2769

Garimella, S., Richards, D. E. and Christensen, R. N. 1988. Experimental investigation of heat transfer in coiled annular ducts. *J. Heat Mass Transfer*, **37**, 329–336

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

Karahalios, G. T. 1990. Mixed-convection flow in a heated curved pipe with core. *Phys. Fluids A*, **2**, 2164–2175

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

Park, S. O. and Choi, H. K. 1993. Mixed-convection flow in a curved annulus—Effect of radius ratio. *Phys. Fluids A. Fluid Dynam.*, **5**, 1843–1845

Rippel, G. R., Eidt, C. R. and Jornan, H. B. 1966. Two-phase flow in a coiled tube. *Ind. Eng. Chem.*, **5**, 32–39

Shah, R. K. and Joshi, S. D. 1987. Convective heat transfer in curved ducts. In *Handbook of Single-Phase Convective Heat Transfer—1987*, S. Kakac, R. K. Shah, and W. Hung (eds.), Wiley Interscience, New York, Chapter 3

Srinivasan, P. S., Nandapurkar, S. S. and Holland, F. A. 1970. Friction factors for coils. *Trans. Inst. Chem. Eng.*, **48**, T156–T161

Xin, R. C., Awwad, A., Dong, Z. F., Ebadian, M. A. and Soliman, H. M. 1996. An investigation and comparative study of the pressure drop in air–water two-phase flow in vertical helicoidal pipes. *Int. J. Heat Mass Transfer* **39**, 735–743