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Air–Water Two-Phase Pressure Drop in U-Type Wavy Tubes

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Two-phase frictional performance of air–water mixture flow in six horizontal U-type wavy tubes is presented. The inner diameters of the wavy tubes are 5.07 and 8.29 mm, whereas the curvature ratios span from 3.94 to ∼7.87. The two-phase superficial velocities for air and water are in the range of $U_{L,S}$ = 0.02–0.7 m/s and $U_{G,S}$ = 0.15–60 m/s. The measured pressure loss in bend included the loss in U bends and the loss caused by the distorted flow in the downstream straight tube. This leads to the definition of the equivalent frictional two-phase pressure gradient in the U bend. The ratio between the two-phase pressure gradient in the U-bend and the two-phase pressure gradient in the upstream straight tube is found in the range of 1.5–3 for most of the data. The ratios increase with gas quality due to consecutive accelerating/deaccelerating phenomenon caused by the wavy tube. The frictional two-phase multiplier in the U bend can be correlated by the use of the Chisholm correlation. By introduction of the Martinelli parameter and the liquid Froude number to the Chisholm correlation, a new correlation is proposed that can describe the present $\phi^2_{B,L}$ data with a mean deviation of 13.9%.

Nomenclature

C	=	constant in Chisholm[21] correlation
D	=	internal diameter of tube, m
Dn	=	new Dean[1] number, $Re/(2R/D)$
dP_B/dz	=	pressure gradient in U bend, N/m
Fr	=	Froude number, $U^2_{L,S}/gD$
f	=	friction factor
G	=	mass flux, kg/m$^2\cdot$s
g	=	acceleration of gravity, m/s^2
L	=	spacer length, m
L_L	=	total spacer length, m
L_S	=	straight length in the upstream for pressure drop measurement, m
L_{st}	=	total straight length in the test section, m
R	=	radius of centerline of bend, m
Re	=	Reynolds number, $\rho U_m D/\mu$
$U_{G,S}$	=	superficial gas velocity, m/s
$U_{L,S}$	=	superficial liquid velocity, m/s
U_m	=	mean axial velocity, m/s
X	=	Martinelli parameter
x	=	gas quality
ΔP_S	=	pressure drop across the straight test section, Pa
ΔP_T	=	total pressure drop across the test section, Pa
μ	=	viscosity, Ns/m^2
ρ	=	density, kg/m^3
$\phi_{B,L}$	=	two-phase frictional multiplier in U bend based on liquid flow alone

Subscripts

B	=	U bend
C	=	curved section
D	=	downstream
G	=	gas-phase flow alone
L	=	liquid-phase flow only
S	=	straight tube
U	=	upstream

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Introduction

FLOW in curved channels has many applications in engineering practice. The curved channels can be in helical, spiral, and U-type return bend forms. In curved tubes, the centrifugal force drives the more rapid fluid in the concave part of the curve channel while the fluid in the convex part is slowing down, causing a secondary flow at right angle to the main flow in the tube.[1–3] The magnitude of such secondary flows becomes less apparent with an increase of bend radius R and with a decrease of fluid velocity. The flow condition distorted by the induced secondary flow persists at a downstream distance of more than 50 tube diameters D for single-phase flow[4] and of $70D$ for two-phase flow.[3] Because of the disturbance caused by the secondary flow, the friction factor and, therefore, the pressure drop for flow in curved tubes were shown to be greater than those for flow in straight tubes of laminar flow[5] and turbulent flow.[4] Very recently, Cho and Tae[6,7] investigated the effect of oil on the condensation and evaporation heat transfer coefficients for R-22 and R-407C inside a microfin tube with a U-type return bend. Their results indicated that the local heat transfer coefficients of R-22 and R-407C for the condensation and evaporation at the downstream straight sections of $48D$ and $30D$ were larger than those of upstream straight sections by 33 and 21%, respectively. The reason is the presence of disturbance caused by the secondary flow in the U bend that was carried into the downstream straight section.

For typical heating, ventilation, air conditioning, and refrigeration (HVAC&R) applications, the exploitation of the consecutive U-type wavy tubes (hairpins) is very common. The higher frictional loss in the consecutive U-type wavy tubes may significantly affect the overall efficiency in the refrigerant system. As a consequence, the knowledge of the frictional performance of a U-type wavy tube with consecutive 180-deg return bends is very important for the design of an air-cooled heat exchanger. There are some investigations relevant to this subject, but most of the previous studies were associated with helical coils and a single 180-deg return bend. For instance, Awwad et al.[8,9] utilized the Martinelli parameter X to correlate the two-phase pressure drop data in helical coils and proposed an empirical correlation as $\Phi^2_L = \text{function}(2R/D,\ X,\ U^2_{L,S}/gD)(1+12/X+1/X^2)$, where R is the radius of the centerline of the bend, $U_{L,S}$ is the superficial liquid velocity, and g is the acceleration of gravity. Although there are a large number of investigations focusing on two-phase pressure drop in straight tubes, unfortunately, two-phase pressure drop data in U-type wavy tubes are not available. Only some models and correlations are available for two-phase flow in U-type return tubes. For instance, Geary[10] proposed a correlation of the two-phase pressure drop in return bends based on his R-22 data conducted in return bends with tube diameter of 11.4 mm and curvature ratios from 2.2 to 6.7. Travis and Rohsenow[11] conducted R-12 experiments in return bends with tube diameter of 8 mm, with curvature ratios of 3.17 and 6.35. The resulting two-phase pressure drops were observed to algebraically increase with increasing total mass flux G and gas quality x and decreasing bend radius. Kim et al.[12] reported a two-phase pressure drop of R-12 with and without the presence of lubrication oil in a return bend. The bend has a diameter of 8.7 mm and a curvature ratio ($2R/D$) of 4.02. The resulting local pressure gradient at the bend is five times larger than that at straight tube. This ratio is increased with oil concentration. These reported data were mainly conducted in larger-diameter tubes ($D > 8$ mm).

Recently, in the application of HVAC&R, small-diameter tubes have become preferable[13,14] because of less inventory, better air-side heat transfer performance, and probable smaller air-side drag. The U-type wavy tubes in air-cooled heat exchangers usually have a spacer length L between two consecutive 180-deg return bends. Therefore, the purpose of this study is to investigate the two-phase frictional characteristics of the consecutive U-type wavy tubes having 5.07- and 8.29-mm diam with the influences of the ratio of curvature radius and the ratio of the spacer length to the tube diameter (L/D), as well as the other significant dimensionless parameters.

Experimental Method

In this study, air and water are used as the working fluids because air and water have different physical properties. The test rig is, therefore, designed to conduct tests with air–water two-phase mixtures, as shown in Fig. 1. Air is supplied from an air compressor and then stored in a compressed-air storage tank. Airflow through a pressure reducer, depending on the mass flux range, is measured by an Aalborg® mass flow meter. The water flow loop consists of a variable speed gear pump that delivers water. The mixer was designed to provide better uniformity of the flow stream. The inlet temperatures of air and water were conducted near 25°C. For the measurement of the water flow rate, three very accurate Yokogawa flow meters with different applicable flow ranges are installed downstream of the gear pump. The accuracy of the air and water mass flow meters is within ±0.2% of the test span. The pressure drop of the air–water mixtures was measured with a Yokogawa EJ110 differential pressure transducer. The holes of the pressure taps are drilled vertically to the test tubes with a hole diameter of 0.5 mm. Resolution of this pressure differential transducer is ±0.5% of the measurements. Validation of the present test setup by single-phase pressure drops for air and water alone against the Reynolds number had been demonstrated in a previous study.[15] Leaving the test section, the air–water mixture was separated by an open water tank in which the air is vented and the water is recirculated. The air and water temperatures were measured by resistance temperature device (Pt100Ω) having a calibrated accuracy of 0.1 K (calibrated by Hewlett–Packard quartz thermometer probe with quartz thermometer, model 18111A and 2804A). A detailed description of the test apparatus and the estimated uncertainties of the measurements had been previously reported.[14,15] The range of the mixture mass flux G is between 100 and 700 $kg/m^2 \cdot s$. The two-phase superficial velocities for air and water tests are in the range of $U_{L,S} = 0.02$–0.7 m/s and $U_{G,S} = 0.15$–60 m/s. The test tubes are insulated and arranged in a horizontal position, such that only the frictional pressure drop is counted. A total of six copper tubes having inner diameters D of 5.07 and 8.29 mm are used for testing. Each U-type wavy pipe contains nine constant radius undulated pipe bends, as shown in Fig. 1. Further relevant geometries such as radius of the return bend R, curvature ratio $2R/D$, tube inside diameter D, and spacer length L are given in Table 1.

A straight entrance length of $100D$ is located at the upper stream of the straight test section to achieve a fully developed flow condition for measurement. A differential pressure transducer is used

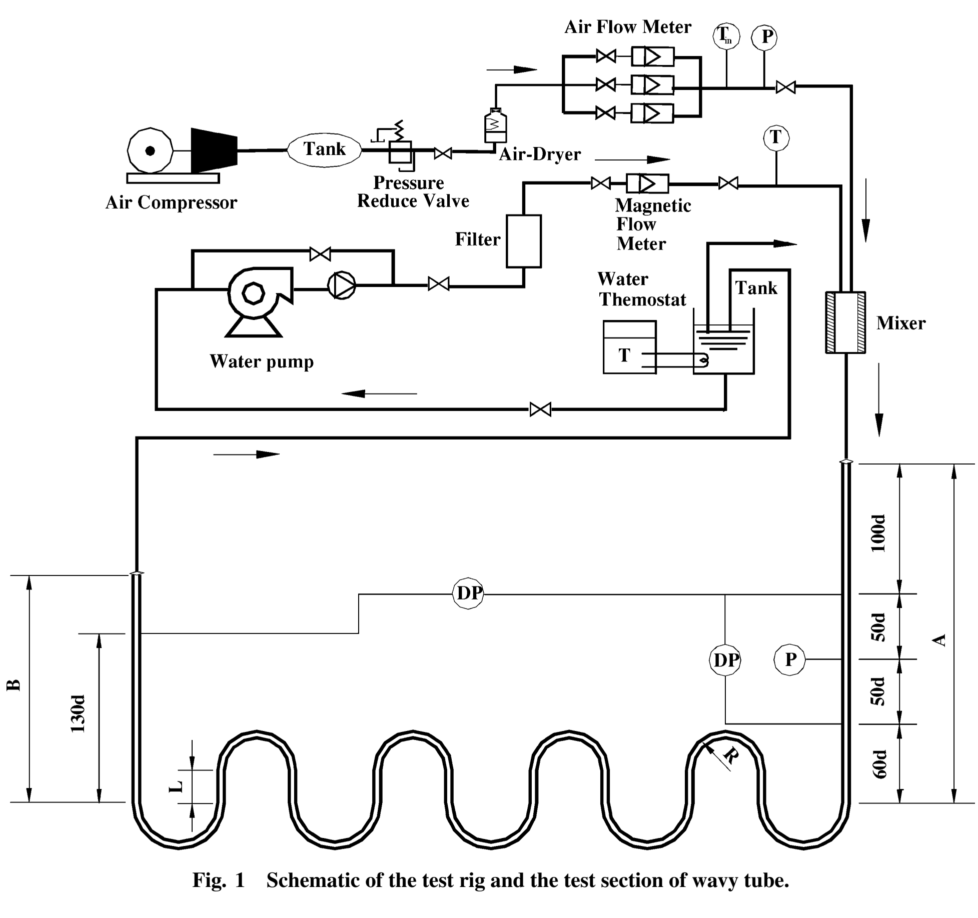


Fig. 1 Schematic of the test rig and the test section of wavy tube.

Table 1 Geometric parameters of the test sections and the test points

	Test points					
Parameter	$D = 5.07$ mm			$D = 8.29$ mm		
R, mm	10	13	17.5	20	25	30
L, mm	30	24	22	18	16	24
$2R/D$	3.94	5.13	6.90	4.83	6.03	7.24
L/D	5.92	4.73	4.34	2.17	1.93	2.90
Data points	50	50	50	41	44	44

to measure the pressure drop ΔP_S across the upstream straight test section ($L_S = 100D$) to serve as a reference for the comparison of the pressure gradient between the U bend and the straight tube. A straight length of $130D$ is directly connected to the U-bend outlet for the flow recovery. Also, the other differential pressure transducer is utilized to measure the total pressure drop ΔP_T, which includes the loss of the wavy section and the loss from the straight portions of the upstream ($L_U = 160D$) and downstream ($L_D = 130D$) straight tubes. Resolution of the pressure differential transducers is 0.3% of the measurements.

The single- and two-phase pressure drop gradients in U bend of the wavy tubes are calculated by subtraction of the equivalent straight tube pressure drop having the length ($L_{\mathrm{st}} = L_U + 8L + L_D$) from the measured total pressured drop ΔP_T and then division by the total axial length of the nine U bends ($L_C = 9\pi R$). Therefore, the total pressure loss gradient due to the U bend in the wavy tube can be expressed as

$$\frac{\mathrm{d}P_B}{\mathrm{d}z} = \frac{\Delta P_T - (\Delta P_S/L_S)L_{\mathrm{st}}}{L_C} \tag{1}$$

The equivalent bending friction factor, $f_B = (\mathrm{d}P_B/\mathrm{d}z)/(2\rho U_m^2/D)$ is then calculated for single-phase flow in the U bend of the wavy tube, where U_m is the mean axial velocity in the tube and ρ is the fluid density.

The Martinnelli approach can be applied to the reduction of the two-phase flow data in curved pipes (see Awwad et al.[8,9]). The frictional two-phase pressure gradient is related to that of gas- or liquid-phase flowing alone in the same curved pipe. The results of this study are presented in terms of the two-phase frictional multiplier based on pressure gradient for liquid alone $\phi_{B,L}$ and the Martinelli parameter X_B, defined by the pressure gradient ratio of liquid-phase flow alone ($\mathrm{d}P_L/\mathrm{d}z$) to gas-phase flow alone ($\mathrm{d}P_G/\mathrm{d}z$) in the same U bend:

$$\phi_{B,L}^2 = \frac{\mathrm{d}P_B}{\mathrm{d}z} \bigg/ \frac{\mathrm{d}P_L}{\mathrm{d}z} \tag{2}$$

$$X_B^2 = \frac{\mathrm{d}P_L}{\mathrm{d}z} \bigg/ \frac{\mathrm{d}P_G}{\mathrm{d}z} \tag{3}$$

Uncertainties of the single-phase friction factor f_B and the two-phase multipliers are estimated by the method suggested by Moffat.[16] The uncertainties of f_B are from 1.3 to 6.4% and range from 3.2 to 11.5% for $\phi_{B,L}^2$. The highest uncertainties were associated with the lowest velocities.

Results and Discussion

The single-phase pressure drop data were conducted from the U-type wavy tubes with water as the working fluid in the test rig. Shown in Fig. 2, the test results of the equivalent bending friction factor f_B were previously reported by Chen et al.[15,17] Measured single-phase frictional data and the data set of Popiel and Wojtkowiak[18] in U-type wavy pipes were correlated to form a friction factor correlation[15,17] with a mean deviation of 5.6%. Note that the mean deviation is

$$\frac{1}{N}\left(\sum_{1}^{N} \frac{|\Delta P_{\mathrm{pred}} - \Delta P_{\mathrm{exp}}|}{\Delta P_{\mathrm{exp}}}\right) \times 100\%$$

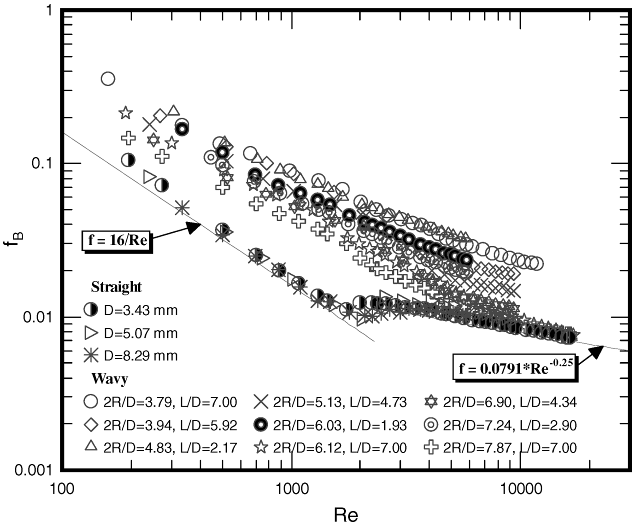


Fig. 2 Friction factor for straight tubes and U bend in wavy tubes.

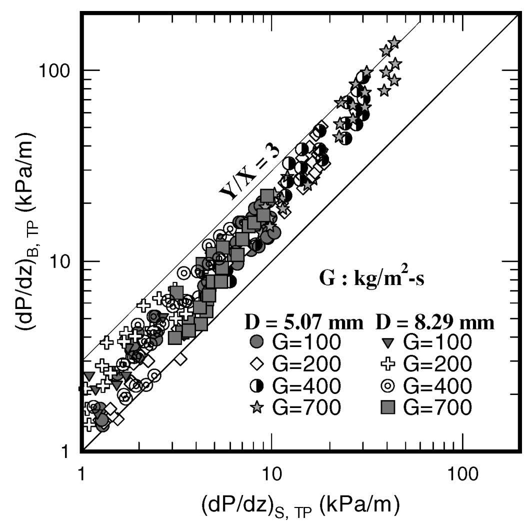


Fig. 3 Two-phase pressure gradient in U bend of wavy tubes vs two-phase pressure gradient in straight tube.

This correlation is utilized as a base to correlate the two-phase pressure drop data in the U bend of the wavy pipes in this study, that is,

$$f_B = (16/Re)[1 + 29\exp(-2R/D)]\exp[A + (L/D)B] \tag{4}$$

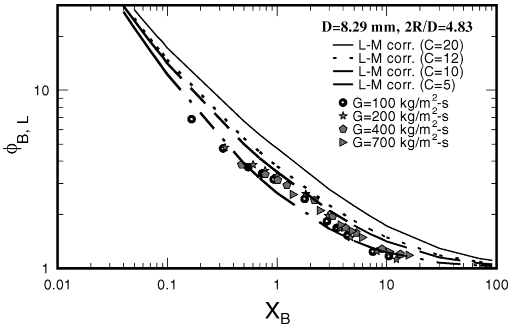
where $A = 0.07 + 0.04\,\ln(Dn)^2$, $B = 0.36 - 0.035\,\ln Re^{0.9} - 0.0145(L/D)^{2.5} + 0.005(L/D)^3$, $Dn = Re/(2R/D)$, and $Re = \rho U_m D/\mu$.

The two-phase pressure gradient in the U bend can be estimated by the use of the correlation of two-phase multipliers developed for straight tubes. Notice that the evaluations of the single-phase pressure gradient for liquid-phase flow alone, $\mathrm{d}P_L/\mathrm{d}z$, shown in Eq. (2), employ the friction factor correlation, Eq. (4). Hence, the corresponding pressure gradients in the U bend of the wavy channels for liquid- and gas-phase flow alone are given, respectively, as follows:

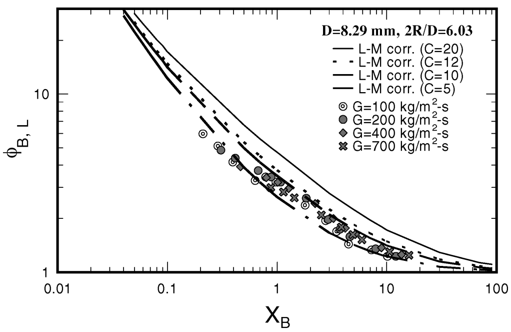
$$\frac{\mathrm{d}P_L}{\mathrm{d}z} = \frac{2f_L\rho_L U_{L,S}^2}{D} \tag{5}$$

$$\frac{\mathrm{d}P_G}{\mathrm{d}z} = \frac{2f_G\rho_G U_{G,S}^2}{D} \tag{6}$$

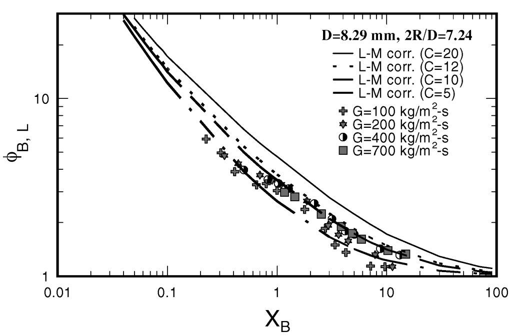
The two-phase pressure gradient in the bending section, $\mathrm{d}P_B/\mathrm{d}z$, can be calculated by Eq. (1) from the measurements. Figure 3 shows



a) 2*R*/*D* = 4.83



b) 2*R*/*D* = 6.03



c) 2*R*/*D* = 7.24

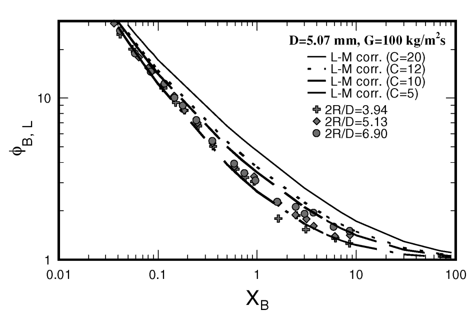
Fig. 4 X_B **vs** $\phi_{B,L}$ **with the effect of** ***G*** **for different 2*R*/*D*, *D* = 8.29 mm.**

that the ratio between the two-phase pressure gradient in the wavy bend and the two-phase pressure gradient in the straight tube for most of the data is found in the range of 1.5–3. In general, at a given mass flux, a detectable increase for the ratios is observed with an increase of quality, whereas a slight increase of the ratio with the smaller tube diameter is seen. As pointed out by Chen et al.,[19] who conducted two-phase flow visualization experiments across a 180-deg return bend inside a 6.9-mm-diam tube, a consecutive deaccelerating and accelerating of the two-phase flow is seen as flow across the return bend. This phenomenon becomes more and more pronounced with the increase of gas phase (or gas quality). This phenomenon is less pronounced for single-phase fluid or at low-quality regions because of the continuum. One of their important findings is that the stratified flow at lower mass flux and lower quality in the downstream, just after the return bend, is briefly turned into annular flow and then changed to stratified flow in the downstream region. Analogous findings are also reported by Wang et al.[20] for return bends having tube diameters of 3 and 7 mm. They also provided a quantitative description of the influential length of the annular flow pattern downstream of the return bend. It is well known that the frictional pressure gradient for annular flow is much greater than that of the stratified flow. As a consequence, the severe accelerating/de-accelerating of the two-phase flow at the high-quality region and the stratified flow with lower mass flux and quality entering the wavy tube result in a significant increase of the pressure gradient ratios.

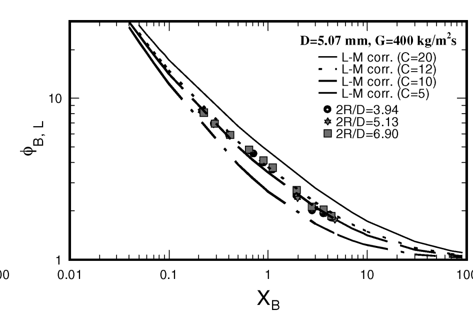
The data of a two-phase multiplier $\phi_{B,L}$ vs the Martinelli parameter X_B for the effects of mass flux G ($D = 8.29$ mm) and curvature $2R/D$ ($D = 5.07$ mm) are shown in Figs. 4 and 5, respectively. For the purpose of comparison, the prediction lines by the Chisholm correlation[21] are also shown in Figs. 4 and 5:

$$\phi_{B,L}^2 = 1 + C/X_B + 1\Big/X_B^2 \tag{7}$$

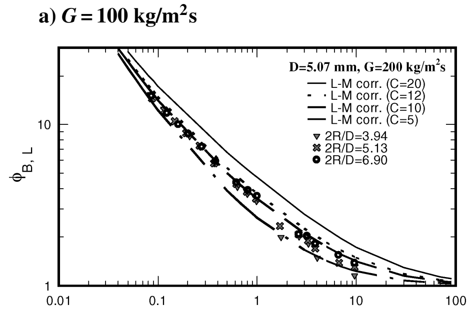
The constants $C = 5$, 10, 12, and 20 are for the different laminar and turbulent flow conditions of gas and liquid phases. In general, the effect of mass flux is relatively small for a mass flux higher than that of 200 kg/m$^2\cdot$s, as shown in Fig. 4. A noticeable influence of the mass flux is seen when $X_B > 0.4$ and $G = 100$ kg/m$^2\cdot$s. For a given value of X_B, one can clearly see that the multiplier parameters $\phi_{B,L}$ for higher mass flux are greater than those of $G = 100$ kg/m$^2\cdot$s. This phenomenon is analogous to that of a smooth straight tube. Wang et al.[22] had clearly demonstrated that this result is associated



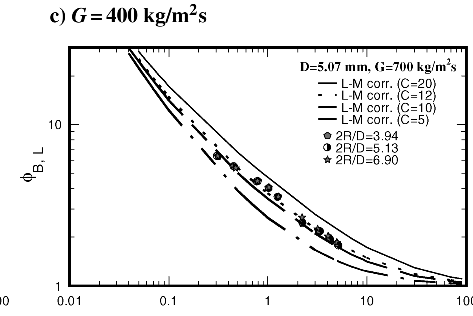
a) *G* = 100 kg/m^{2}s



c) *G* = 400 kg/m^{2}s



b) *G* = 200 kg/m^{2}s



d) *G* = 700 kg/m^{2}s

Fig. 5 X_B **vs** $\phi_{B,L}$ **with the effect of 2*R*/*D* for different *G*, *D* = 5.07 mm.**

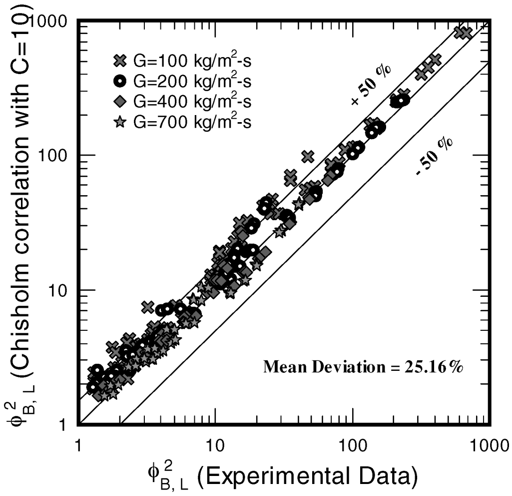


Fig. 6 Predictions of Chisholm correlation[21] with $C = 10$ vs experimental data.

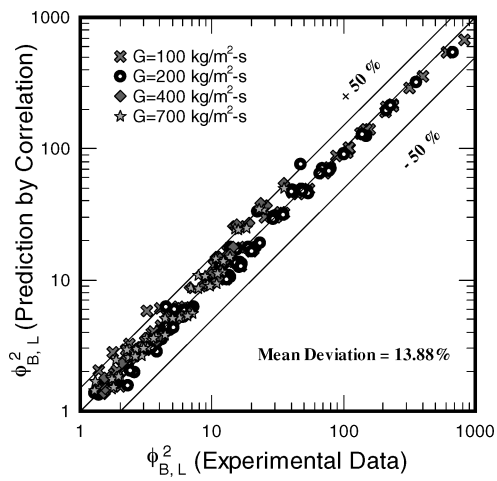


Fig. 7 Predictions of the proposed correlation, Eq. (8), vs experimental data.

with the flow pattern transition of stratified flow to wavy/annular flow. Also depicted in Figs. 5a–5d are the comparatively small influence of the curvature ratio, except at $G = 100$ kg/m$^2 \cdot$ s. The results are not surprising because this influence had been implicitly included in the definition of $\phi_{B,L}$ and X_B. X_B has implemented the influence of gas quality, whereas $\phi_{B,L}$ automatically accounts for the effect of curvature ratio in single-phase part.

Figure 6 shows the comparison of the present $\phi_{B,L}^2$ data with the predictions of the Chisholm correlation[21] with $C = 10$ in Eq. (7). Generally, this correlation gives a fair prediction with a mean deviation of 25.16%, but most of the data are overpredicted. As shown in Figs. 4–5, the mass flux G and Martinelli parameter X_B were observed to have influences on the two-phase multiplier $\phi_{B,L}$. Therefore, it would be more rational to modify Eq. (7) by introducing X_B and the liquid Froude number ($Fr = U_{L,S}^2/gD$) (both parameters varied with the mass flux and quality) to the Chisholm correlation.[21] The proposed correlation for the wavy tube is given as follows:

$$\phi_{B,L}^2 = 0.9116 X_B^{-0.0546} Fr^{0.0785}\left(1 + 10/X_B + 1\big/X_B^2\right) \qquad (8)$$

Figure 7 shows the comparison of $\phi_{B,L}^2$ between the predictions of Eq. (8) and the present data having a mean deviation of 13.9%. Generally, the present correlation gives a very good agreement with the experimental results. From the results described earlier, the frictional pressure gradient of two-phase flow for U bends in a wavy tube can be obtained by the following steps:

1) Use the two-phase flow conditions and the given geometric parameters of a wavy tube to calculate the Martinelli parameter X_B [Eqs. (3) and (4)] and the liquid Froude number Fr.

2) Calculate the frictional mutiplier $\phi_{B,L}^2$ from Eq. (8) by the obtained X_B and Fr in step 1.

3) Use the friction factor, Eq. (4), to calculate the frictional pressure gradient $\mathrm{d}P_L/\mathrm{d}z$ for liquid flow alone in the U bend from Eq. (5).

4) Use the obtained $\phi_{B,L}^2$ and $\mathrm{d}P_L/\mathrm{d}z$ to calculate the frictional two-phase pressure gradient in the U bend of wavy tubes by Eq. (2).

Conclusions

Measurements of frictional pressure drops for a two-phase air–water mixture flowing in six U-type wavy tubes were conducted. Results of this study are summarized as follows:

1) The ratio between the two-phase pressure gradient in the U bend and the two-phase pressure gradient in straight tube is found to be in the range of 1.5–3 for most of the data. For a given mass flux, the ratio increases with the gas quality due to the consecutive accelerating/de-acclerating phenomenon caused by the wavy tube.

2) The frictional two-phase multiplier in the U bend is found to be related to the Lockhart–Martinelli relationship. The Chisholm[21] correlation with $C = 10$ in Eq. (7) gives a fair prediction with a mean deviation of 25.2%.

3) The two-phase multiplier $\phi_{B,L}$ also depends on the total mass flux. The effect of mass flux becomes significant for $X_B > 0.4$.

4) By the introduction of X_B and Froude number Fr to the Chisholm correlation, a new correlation, Eq. (8), is proposed that can describe the present $\phi_{B,L}^2$ data with a mean deviation of 13.9%.

Acknowledgments

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References

[1]Dean, W. R., "Note on the Motion of Fluid in a Curved Pipe," *Philosophical Magazine*, Vol. 4, No. 2, 1927, pp. 208–223.

[2]Barua, S. N., "On Secondary Flow in Stationary Curved Pipes," *Journal of Applied Mathematics and Mechanics*, Vol. 16, No. 1, 1963, pp. 61–70.

[3]Cheng, K. C., and Yuen, F. P., "Flow Visualization Studies on Secondary Flow Patterns in Straight Tubes Downstream of a 180 deg Bend and in Isothermally Heated Horizontal Tubes," *Journal of Heat Transfer*, Vol. 109, No. 1, 1987, pp. 49–61.

[4]Ito, H., "Pressure Losses in Smooth Pipe Bends," *Journal of Basic Engineering*, Vol. 82, No. 1, 1960, pp. 131–143.

[5]Manlapaz, R. L., and Churchill, S. W., "Fully Developed Laminar Flow in a Helical Coiled Tube of Finite Pitch," *Chemical Engineering Communications*, Vol. 7, No. 1, 1980, pp. 57–58.

[6]Cho, K., and Tae, S. J., "Evaporation Heat Transfer for R-22 and R-407 Refrigerant-Oil Mixture in a Microfin Tube with a U-bend," *International Journal of Refrigeration*, Vol. 23, No. 2, 2000, pp. 219–231.

[7]Cho, K., and Tae, S. J., "Condensation Heat Transfer for R-22 and R-407 Refrigerant-oil Mixtures in a Microfin Tube with a U-bend," *International Journal of Heat and Mass Transfer*, Vol. 44, No. 11, 2001, pp. 2043–2051.

[8]Awwad, A., Xin, R. C., Dong, Z. F., Ebadian, M. A., and Soliman, H. M., "Flow Patterns and Pressure Drop in Air–Water Two-Phase Flow in Horizontal Helicoidal Pipes," *Journal of Fluids Engineering*, Vol. 117, No. 4, 1995, pp. 720–726.

[9]Awwad, A., Xin, R. C., Dong, Z. F., Ebadian, M. A., and Soliman, H. M., "Measurement and Correlation of the Pressure Drop in Air–Water Two-Phase Flow in Horizontal Helicoidal Pipes," *International Journal of Multiphase Flow*, Vol. 21, No. 4, 1995, pp. 607–619.

[10]Geary, D. F., "Return Bend Pressure Drop in Refrigeration Systems," *ASHRAE Journal*, Vol. 81, No. 1, 1975, pp. 250–265.

[11]Travis, D. P., and Rohsenow, W. M., "The Influence of Return Bends on the Downstream Pressure Drop and Condensation Heat Transfer in Tubes," *ASHRAE Transactions*, Vol. 79, Pt. 1, 1973, pp. 129–137.

[12]Kim, J. S., Katsuya, N., Masafumi, K., Kouichrio, K., and Toshiaki, H., "Influence of Oil on Refrigerant Evaporator Performance—4th Report: Flow Regime and Pressure Drop in Return Bend," *Transactions of the Japanese Association of Refrigeration*, Vol. 6, No. 1, 1989, pp. 79–89.

[13]Chen, I. Y., Yang, K. S., Chang, Y. J., and Wang, C. C., "Two-Phase Pressure Drop of Air–Water and R-410A in Small Horizontal Tubes," *International Journal of Multiphase Flow*, Vol. 27, No. 7, 2001, pp. 1293–1299.

[14]Chen, I. Y., Yang, K. S., and Wang, C. C., "Two-Phase Frictional Pressure Drop Correlations for Small Tubes," *Journal of Thermophysics and Heat Transfer*, Vol. 15, No. 4, 2001, pp. 409–415.

[15]Chen, I. Y., Lai, Y. K., and Wang, C. C., "Two-Phase Friction Pressure Drop of Small Diameter U-Type Wavy Tube," AIAA Paper 2002-3021, June 2002.

[16]Moffat, R. J., "Describing the Uncertainties in Experimental Results," *Experimental Thermal and Fluid Science*, Vol. 1, No. 1, 1988, pp. 3–17.

[17]Chen, I. Y., Lai, Y. K., and Wang, C. C., "Frictional Performance of Small Diameter U-Type Wavy Tubes," *Journal of Fluids Engineering*, Vol. 125, No. 4, 2003, pp. 880–886.

[18]Popiel, C. O., and Wojtkowiak, J., "Friction Factor in U-Type Undulated Pipe," *Journal of Fluids Engineering*, Vol. 122, No. 2, 2000, pp. 260–263.

[19]Chen, I. Y., Yang, Y. W., and Wang, C. C., "Influence of Horizontal Return Bend on the Two-Phase Flow Pattern in a 6.9-mm Diameter Tube," *Canadian Journal of Chemical Engineering*, Vol. 80, No. 3, 2002, pp. 478–484.

[20]Wang, C. C., Chen, I. Y., Yang, Y. W., and Hu, R., "Influence of Horizontal Return Bend on the Two-Phase Flow Pattern in Small Diameter Tubes," *Experimental Thermal and Fluid Science*, Vol. 28, Nos. 2–3, 2004, pp. 145–152.

[21]Chisholm, D., "A Theoretical Basis for the Lockhart–Martinelli Correlation for Two-Phase Flow," *International Journal of Heat and Mass Transfer*, Vol. 10, No. 10, 1967, pp. 1767–1778.

[22]Wang, C. C., Chiang, C. S., and Lu, D. C., "Visual Observation of Flow Pattern of R-22, R-134a, and R-407C in a 6.5 mm Smooth Tube," *Experimental Thermal and Fluid Science*, Vol. 15, No. 4, 1997, pp. 395–405.