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Two-Phase Pressure Drop of Air–Water in Small Horizontal Tubes

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Two-phase flow pressure drops of air–water in small horizontal smooth tubes of 1.02, 3.17, 5.05, and 7.02 mm are reported. The data are compared with homogeneous, slug, and annular flow models, as well as the commonly used empirical correlations. The tested results indicate that the empirical correlations available in the literature failed to predict the data. The slug flow and annular flow models give fair predictions with their corresponding flow regime data. The homogeneous model shows better predictive ability as compared to other empirical correlations. However, overpredictions of homogeneous and annular models are observed for most of the 1.02- and 3.17-mm data. Thus, modifications of the homogeneous model and the Friedel correlation are made by introducing the Bond number, Weber number, and other significant dimensionless groups to correlate the test data. The modified Friedel correlations and the modified homogeneous model show good agreement with the present data, as well as with five available data sets of ammonia and refrigerants from the literature.

Nomenclature

Bo	=	Bond number, $g(\rho_L - \rho_g)(d/2)^2/\sigma$
C	=	constant in Chisholm[7] correlation
Co	=	void distribution parameter
d	=	inside diameter of the tube, m
$\mathrm{d}P_f/\mathrm{d}Z$	=	measured two-phase frictional pressure gradient, N/m^3
$\mathrm{d}P_{f,g}/\mathrm{d}Z$	=	frictional pressure gradient for gas flowing alone, N/m^3
$\mathrm{d}P_{f,L}/\mathrm{d}Z$	=	frictional pressure gradient for liquid flowing alone, N/m^3
$\mathrm{d}P_{f,L0}/\mathrm{d}Z$	=	frictional pressure gradient for total flow assumed liquid, N/m^3
Fr	=	Froude number, $G^2/(gd\rho_m^2)$
f	=	friction factor
G	=	total mass flux, kg/m$^2\cdot$s
g	=	gravitational acceleration, m/s^2
$\dot{m}_a$	=	airflow rate, kg/s
$\dot{m}_w$	=	water flow rate, kg/s
P	=	pressure, N/m^2
Re_G	=	superficial gas Reynolds number, Gxd/μ_G
Re_{L0}	=	liquid Reynolds number based on the total mass flux, Gd/μ_L
U_b	=	bubble velocity, gas phase, m/s
U_{GS}	=	superficial velocity, gas phase, m/s
U_{LS}	=	superficial velocity, liquid phase, m/s
We	=	Weber number, $G^2d/(\rho_m\sigma)$
X	=	Martinelli parameter
x	=	vapor quality
z	=	tube axial direction, m
α	=	void fraction
μ	=	dynamic viscosity, N$\cdot$s/m^2
ρ	=	density, kg/m^3
ρ_m	=	mixture density $[x/\rho_G + (1-x)/\rho_L]^{-1}$, kg/m^3
σ	=	surface tension of liquid, N/m
Φ_G^2	=	two-phase friction multiplier for gas flowing alone
Φ_L^2	=	two-phase friction multiplier for liquid flowing alone
$\Omega_{\mathrm{Friedel}}$	=	Friedel pressure drop correction[11] factor defined in Eq. (15)
Ω_{hom}	=	homogeneous pressure drop correction factor defined in Eq. (13)
Ω_{L0}^2	=	two-phase friction multiplier for total flow assumed liquid

Subscripts

f	=	friction
G	=	gas phase only
i	=	interface
L	=	liquid phase only
$L0$	=	total flow assumed liquid phase

Introduction

THE calculation of pressure drop in any two-phase flow system is very important in the design of steam-power and petrochemical plants and refrigeration and air-conditioning systems. Knowledge for predictions of two-phase flow pattern and frictional pressure drop has been greatly improved over the years. Recently, the design of residential air conditioners has employed smaller diameter tubes (6.35 $\sim$ 9.53 mm) to improve the airside performance (lower airside pressure drop and higher heat transfer coefficient) and to reduce the refrigerant charge into the system. Recently, air-conditioning manufacturers began implementing the related application by use of 4 $\sim$ 5 mm diam tubes. In addition, NASA has utilized the two-phase flow concept to design the external active thermal control system for Space Station freedom (SSF).[1] The tube diameters of the cold plates, heat exchangers, and the radiators in the SSF are quite small, that is, 1.27 mm for the heat exchangers, 3.81 mm for the cold plates, and 1.7 mm for the radiator condensation tubes.[1] Characteristics of two-phase flow in small diameter tubes have become important in the design of modern air conditioners and space

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thermal control systems, as well as electronic cooling by heat pipes. Unfortunately, most normally used predictive pressure drop methods are based on experimental data with tube diameters greater than 10 mm. Apparently, these correlations do not account for the surface tension effect that becomes comparatively important in small diameter tubes. Investigations of two-phase frictional performance in small tubes are very limited. Some of the relevant studies are described in the following.

Ungar and Cornwell[2] measured the pressure drop for adiabatic two-phase ammonia flows in small horizontal tubes ($d = 1.46$, 1.78, 2.58, and 3.15 mm) to size the tube diameter for the SSF flow-through radiators. They found that the pressure drops of ammonia two-phase flow in small diameter tubes are significantly lower than the most commonly used correlations. However, their ammonia pressure drop data were well described by the homogeneous model[3] and by the annular flow prediction.[4] Notice that the annular flow model assumes a smooth interfacial frictional factor ($f_i = f_G$). Triplett et al.[5] conducted air–water two-phase experiments in 1.1- and 1.45-mm-diam tubes. For their bubbly and slug flow pressure drop data, the homogeneous mixture model gives fairly good predictions. However, for annular flow data, the homogeneous flow model and other widely used correlations significantly overpredicted the frictional pressure drop.

In view of the previous investigations, it seems that the two-phase frictional characteristics in small diameter tubes are still not fully understood. The existing correlations may fail to predict the frictional pressure drop of small diameter tubes. Hence, the objective of the present study is twofold. First, new test results for small diameter tubes are presented, and second, modified correlations are developed that are able to describe test results for small diameter tubes. Experiments were conducted in the air–water system with identifiable flow patterns in small diameter tubes.

Background

Empirical Correlations

Because the acceleration and gravitational pressure drops can be neglected in adiabatic experiments in horizontal tubes, the measured pressure drop only came from the frictional loss. Lockhart and Martinelli[6] defined the two-phase frictional multipliers. Their data also indicated that the multipliers were a function of the Martinelli parameter alone. However, their data were taken from large diameter tubes and were assumed to be in the annular flow regime. These multipliers are given by

$$\Phi_L^2 = \frac{\mathrm{d}P_f/\mathrm{d}z}{\mathrm{d}P_{f,L}/\mathrm{d}z}, \qquad \Phi_G^2 = \frac{\mathrm{d}P_f/\mathrm{d}z}{\mathrm{d}P_{f,G}/\mathrm{d}z} \tag{1}$$

where $\mathrm{d}P_f/\mathrm{d}z$ is the measured two-phase frictional pressure gradient and $\mathrm{d}P_{f,L}/\mathrm{d}z$ and $\mathrm{d}P_{f,G}/\mathrm{d}z$ are the frictional pressure gradient for liquid and gas of the two-phase mixture flowing alone in the tube, respectively. The Martinelli parameter is defined as

$$X^2 = \frac{\mathrm{d}P_{f,L}/\mathrm{d}z}{\mathrm{d}P_{f,G}/\mathrm{d}z} \tag{2}$$

The relationship of Φ_L^2 and Φ_G^2 to X^2 was originally presented in graphical form, but Chisholm[7] has approximated these relationships by the simple expressions

$$\Phi_G^2 = 1 + CX + X^2, \qquad \Phi_L^2 = 1 + C/X + 1/X^2 \tag{3}$$

Chisholm,[7] depending on whether the liquid and gas phases are laminar or turbulent flow, gives tabular constants for C.

Troniewski and Ulbrich[8] proposed different expressions for describing the two-phase frictional multiplier with the Martinelli parameter. They[8] developed different correlation forms for various ranges of the Martinelli parameter. Though Troniewski and Ulbrich's correlation[8] is more complicated than the Chisholm correlation,[7] this correlation had been selected for the prediction of two-phase pressure drop in the SSF active thermal control system.[1] The predictions by the Troniewski and Ulbrich[8] correlation were consistently found to agree well with ground and microgravity annular flow data.[9,10]

Friedel[11] proposed a method based on a bank of 25,000 data, which is in terms of a multiplier by

$$\Phi_{L0}^2 = \frac{\mathrm{d}P_f/\mathrm{d}z}{\mathrm{d}P_{f,L0}/\mathrm{d}z} \tag{4}$$

where $\mathrm{d}P_{f,L0}/\mathrm{d}z$ is the frictional pressure gradient for total flow assumed liquid. The Friedel correlation had been recommended by Whalley[12] when $(\mu_L/\mu_G) < 1000$. However, the Friedel correlation was found to overpredict significantly the data of smaller liquid mass flux and slightly underpredict the data of higher liquid mass flux in very small tubes.[5]

Flow-Regime-Dependent Models

Typically, there are four primary flow patterns of interest for two-phase flow in tubes. The flow patterns include bubble, stratified, slug, and annular. These flow patterns are referred as flow regimes.[13]

Homogeneous Flow

The homogeneous flow approximation treats the two-phase mixture as a single fluid with mixture properties. The frictional pressure drop is calculated using a standard single-phase pressure drop prediction method. McAdams et al.[3] proposed a simple relation for defining the mixture properties to calculate the two-phase pressure drop. Although the homogeneous flow model was developed for general use, it had been shown[14] to be accurate only for bubbly flow. Recently, the homogeneous flow model was reported to give accurate predictions for bubbly and slug flow data at high liquid mass flux for 1.1- and 1.45-mm tubes.[5]

Slug Flow

A drift-flux model can be used to calculate the pressure drop in slug flow. In this model, the two-phase homogeneous pressure drop prediction method is modified to account for the relative motion between the phases. The void fraction α for a horizontal slug flow has the form[10]

$$\alpha = 1/Co[1 + (U_{LS}/U_{GS})] \tag{5}$$

where Co is the void distribution parameter, and U_{LS} and U_{GS} are the liquid and vapor superficial velocities, respectively. The void fraction distribution parameter can be obtained from experiment using $Co = U_b/(U_{LS} + U_{GS})$, where U_b is the measured axial velocity of the Taylor bubbles. The value of Co was found between to be 0.94 and 1.43 (Ref. 10). Mishima and Hibiki[15] have correlated from air–water flow data for diameter $d = 1.09 - 4.9$ mm, the equation for Co, including the effect of tube diameter, which is given as

$$Co = 1.2 + 0.51e^{-0.691d} \tag{6}$$

where the d is in millimeters. The frictional pressure drop for slug flow can be calculated by[10,16]

$$\left(\frac{\mathrm{d}P}{\mathrm{d}z}\right)_f = 2\left(\frac{f_L}{d}\right)(1-\alpha)\rho_L(U_{LS} + U_{GS})^2 \tag{7}$$

where f_L is the Fanning friction factor for the liquid flowing alone in the tube.

Annular Flow

A pressure drop prediction for annular flow can also be developed from an annular flow model. When the momentum balance on the liquid and gas phases of annular flow with no entrainment and a smooth interface was considered, Collier and Thome[13] obtained

$$\Phi_G^2 = (1/\alpha^{2.5})(f_i/f_G) \tag{8}$$

$$X = [(1-\alpha)^2/\alpha^{2.5}](f_i/f_G) \tag{9}$$

where f_G is the Fanning friction factor for the gas phase flowing alone in the tube. Ungar and Cornwell[2] found that Wallis's[14] interfacial friction factor correlation, $f_i/f_G = 1 + 75(1 - \alpha)$, produces much higher predictions than the measured pressure drop for small tubes. The same form of f_i/f_G equation for an annular flow model, but with a different coefficient and exponent dependence has also been given in Refs. 17–20.

Ungar and Cornwell[2] have plotted f_i/f_G vs void fraction for ammonia two-phase flow in small tube diameters of 1.46–3.15 mm; however, no correlation between the interfacial friction factor and the void fraction was found. Most of their iterated values of f_i/f_G were to be found in the range of 0.5–3.0, which are much smaller than the other reported f_i/f_G values for annular flow. From their discussion, f_i/f_G shows a range of uncertainty in the pressure drop calculation. To use this annular model, a reliable f_i/f_G correlation is required for use over the range of the operating conditions for smaller tubes. In the present study, void fraction is not measured; however, an iteration process is utilized to obtain the values of α and f_i/f_G for each annular flow point. A value of f_i/f_G is initially guessed to solve for α and Φ_G^2 from Eqs. (8) and (9), respectively. The iteration process is repeated until the calculated pressure drop and the measured annular data differ by a very small tolerance (0.0001 value of the measured pressure drop data).

Experiment

The test rig is designed to allow adiabatic flow experiments with air–water mixtures shown in Fig. 1. Air is supplied from an air compressor and then stored in a compressed-air storage tank. Air flows through a pressure reducer and, depending on the mass flux range, is measured by four mass flowmeters (Aalborgr¨, Model GFM 17 and GFM 47). The water flow loop consists of a variable speed gear pump that delivers water to mix with the airflow in the air–water mixer. As can be seen from the enlarged view of Fig. 1, the mixing chamber is fabricated with round perspex tube having an inner diameter of 10 mm and length of 100 mm. There are six stainless steel wire screens equally spaced inside the perspex tube. The screen has 1600 meshes/in.^{2}, and the wire thickness is 0.2 mm. The inlet temperatures of the air–water mixtures are near 25°C. Three very accurate mass flowmeters (Micromotion, Model DS12S-100SU) with different flow ranges are installed downstream of the gear pump. The accuracy of the air and water mass flowmeters is within ±0.2% of the test span. The test tubes are made of round copper tubes having inner diameters of 1.02, 3.17, 5.05, and 7.02 mm, and the corresponding lengths for the pressure drop measurements are 150, 995, 995, and 995 mm, respectively. The pressure drop of the air–water mixtures was measured by a YOKOGAWA EJ110 differential pressure transducer having an adjustable span of 1300–13,000 Pa. 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 0.3% of the measurements.

The mixture leaving the test section was connected to a perspex glass tube having an identical inside diameter with the test section. The glass tube has a length of 100 mm. Observations of flow patterns are obtained from images produced by a microcamera (Nikon FM2). 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). The quality of the air–water ranged from 0.0001 to 0.9, and the total mass flux G ranged from 50 to 3000 kg/m^2 · s for the air–water mixture. Experimental uncertainties of the basic measurements and the derived quantities reported in the present investigation, following the single-sample analysis proposed by Moffat,[21] are given in Table 1.

Results and Discussion

All of the measured air–water pressure drop data are compared with the predictions of empirical correlations of Troniewski and

Table 1 Summary of estimated uncertainties

Primary measurements		Derived quantities		
Parameter	Uncertainty	Parameter	Uncertainty $G = 50$ kg/m^2 · s	Uncertainty $G = 700$ kg/m^2 · s
$\dot{m}_w$, %	0.3–2	G, %	1.1	0.5
$\dot{m}_a$, %	0.5–5	x, %	±3.1	± 2.5
ΔP, %	0.5 ∼ 6	ϕ_L^2, %	±22.5	± 3.3
T, °C	0.1	X, %	±6.4	± 2.8

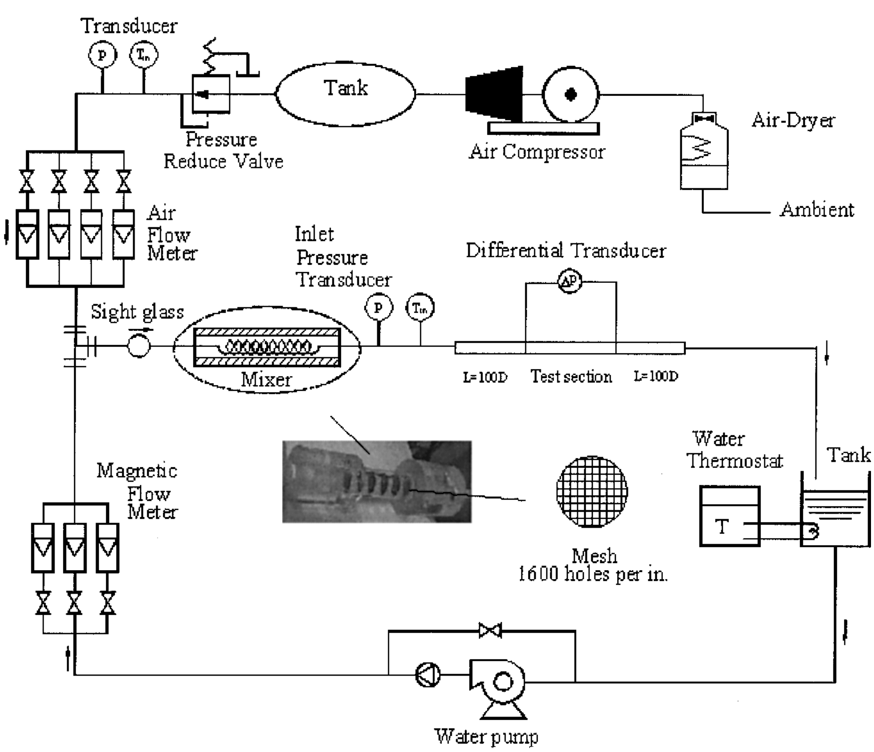

Fig. 1 Air–water two-phase flow test loop.

Ulbrich,[8] Friedel,[11] and Chisholm,[7] and their mean deviations are 276.35, 156.94, and 84.82%, respectively. The mean deviation is calculated by

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

Notice that the aforementioned correlations are flow regime independent correlations. Apparently these correlations failed to predict the data. The huge deviations for these correlations are attributable to that the database they used were mainly for larger diameter tubes. Figure 2 only shows the comparisons of the bubble, slug, and stratified flow data of the 3-, 5-, and 7-mm tubes with the McAdams et al.[3] homogeneous predictions. The corresponding mean deviation shown in Fig. 2 is 21.34%. Note the Beattie–Whalley's mixture viscosity[22] is utilized for the homogeneous predictions. As expected, the homogeneous predictions show very good agreements with bubble and slug flow pattern data. Ungar and Cornwell[2] and Triplett et al.[5] also reported this consistency.

Figure 3 shows the comparison of the homogeneous predictions with all of the present air–water data. The mean deviation for the comparison shown in Fig. 3 is 61.2%. Figure 3 shows that the homogeneous model has better predictive ability as compared to the earlier three empirical correlations. However, overpredictions are observed in Fig. 3 for most of the 1- and 3-mm tube data.

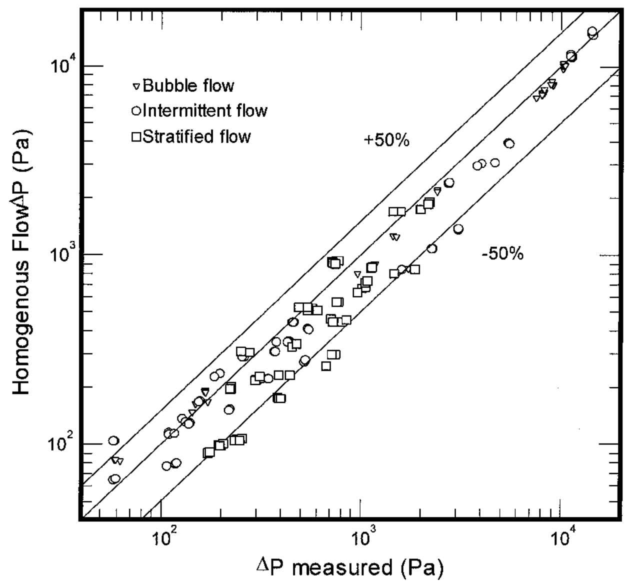

Fig. 2 Comparison of the bubbly, intermittent, and stratified data to homogeneous predictions.

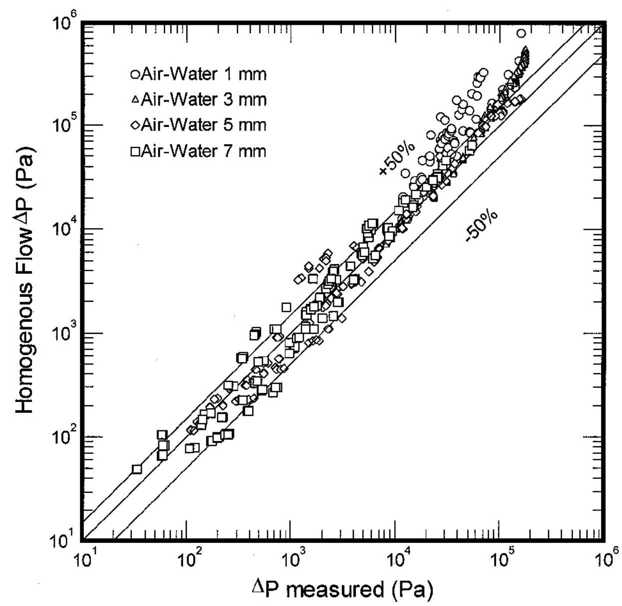

Fig. 3 Comparison of present data with the predictions by homogeneous flow model.

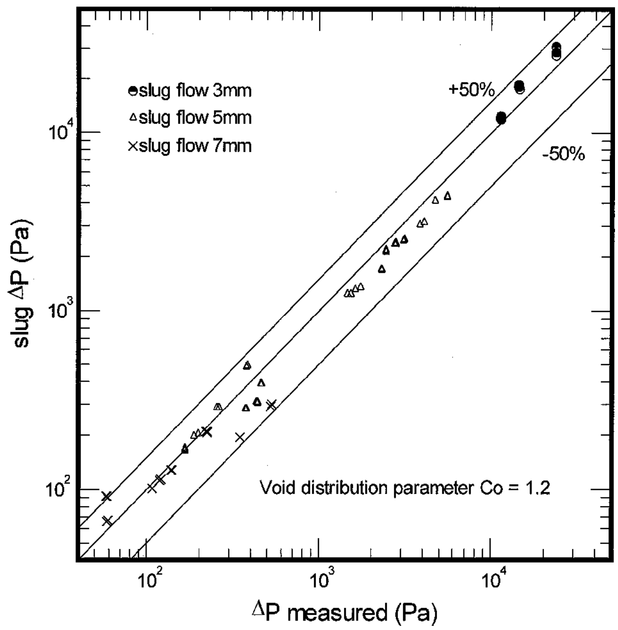

Fig. 4 Comparison of the slug flow data to the predictions by slug flow model.

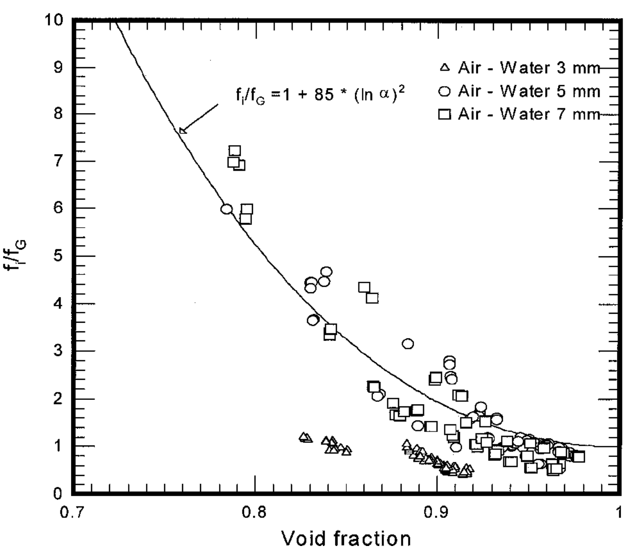

Fig. 5 Interfacial friction factor ratio vs void fraction of annular flow data.

Figure 4 is the comparison between the air–water slug flow data and the slug flow predictions with a best-fit value of $Co = 1.2$. The mean deviation for the comparison shown in Fig. 4 is 17.48%. The results show that the slug flow model has the ability to predict the present slug flow data. Figure 5 shows the friction factor ratio, f_i/f_G against the void fraction for the present annular flow data. Note that most of the values of f_i/f_G are less than 3.0 especially for 3-mm-diam tube. The interfacial frictional factor ratios in the 5- and 7-mm tubes are consistently higher than those of the 3-mm tube. This indicates that the surface tension could tend to smooth out the liquid–vapor interface in 3-mm tube and, thus, decreasing the value of f_i/f_G to near 1.0. A best fit to the f_i/f_G data for 5- and 7-mm tubes in Fig. 5 is correlated as

$$f_i/f_G = 1 + 85(\ln\alpha)^2 \qquad (10)$$

Equation (10) has a mean deviation of 32.45% as compared to the annular flow data for 5- and 7-mm tubes.

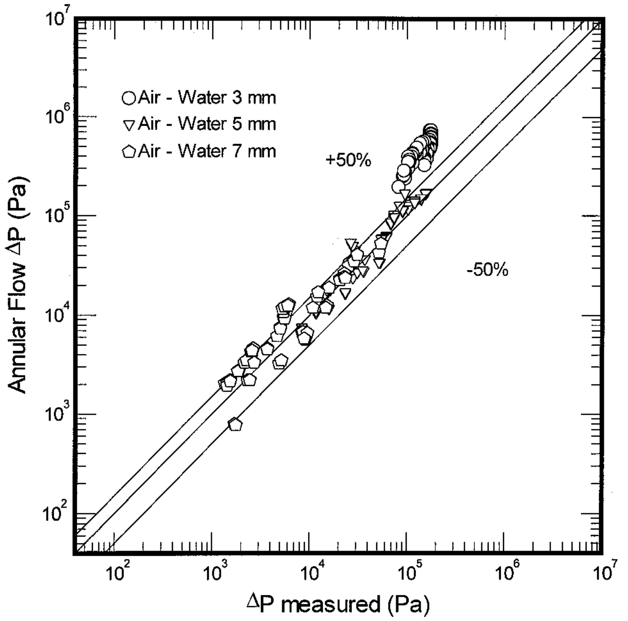

Fig. 6 Comparison of annular flow data to the predictions by annular flow model.

Figure 6 is the comparison between the air–water annular flow data and the annular flow predictions using Eqs. (8) and (10). Overpredictions are observed for the 3-mm tube data. This is because the f_i/f_G for the 3-mm tube cannot be correlated by Eq. (10). It is likely that this deviation for the annular flow data from the homogeneous and annular flow predictions is related to the effect of surface tension σ in very small tubes.

For two-phase flow in small tubes, the effect of the surface tension force should be more significant compared to the gravitational force. Ungar et al.[23] indicated that the criterion to satisfy this balance is for the Bond number equal to unity ($Bo = 1$), where Bond number is defined as

$$Bo = g(\rho_L - \rho_G)[(d/2)^2/\sigma] \tag{11}$$

When the value of Bond number Bo is near or less than 1.0, the stratified flow pattern is not able to exist in most of the two-phase flow conditions. Therefore, Bond number should be included to evaluate the pressure drop in small tubes.

For practical consideration, most commonly used two-phase frictional correlations are usually presented as flow regime independent correlations. To extend the applicability of the existing correlations to smaller diameter tubes, the effects of surface tension σ, tube diameter d, and total mass flux G should be included in the pressure drop prediction. The homogeneous model and the Friedel correlation[11] are then modified with Bond number, Weber number [$We = G^2d/(\rho_m\sigma)$], Reynolds number, and other related significant dimensionless parameters to extend their predictive abilities. Test results of this study (air–water data, 710 points), Chen et al.[24] (R-410A data, 252 points), and Ungar and Cornwell[2] (ammonia data, 134 points) are used to develop the modified correlations. The selection of R-410 and ammonia fluids is due to their diverse difference in properties with air–water. The modified homogeneous model is given as

$$\left(\frac{\mathrm{d}p}{\mathrm{d}z}\right) = \left(\frac{\mathrm{d}p}{\mathrm{d}z}\right)_{\mathrm{hom}} \times \Omega_{\mathrm{hom}} \tag{12}$$

$$\Omega_{\mathrm{hom}} = \begin{cases} 1 + (0.2 - 0.9e^{-Bo}) + \dfrac{48\exp(-\rho_L/30\rho_G)}{Bo^{0.7}Re_{L0}^{0.5}} & \text{for} \quad Bo < 2.5 \\ 1 + \dfrac{We^{0.2}}{e^{Bo^{0.3}}} - 0.9e^{-Bo} & \text{for} \quad Bo \geq 2.5 \end{cases} \tag{13}$$

where $(\mathrm{d}P/\mathrm{d}z)_{\mathrm{hom}}$ is the two-phase pressure gradient predicted by the homogeneous model. Figure 7 presents the comparison between the modified homogeneous predictions and all of the air–water data. The comparison in Fig. 7 gives a mean deviation of 22.31%.

The Friedel correlation[11] is the only correlation that is intended to include the effect of surface tension and the total mass flux by the Weber number and the gravity effect by the Froude number [$Fr = G^2/(gd\rho_m^2)$]. However, the exponents of the dependence of Weber number, 0.035, and Froude number, 0.045, are rather small. For small diameter tubes, it is expected that the effect of surface tension may become more pronounced and the influence of gravity may become less important. Hence, it is very likely that the Friedel correlation may underestimate the influence of surface tension and overestimate the effect of gravity in small diameter tubes. In this connection, a slight modification to the Friedel correlation is proposed that can provide better predictive ability for the Friedel correlation for smaller diameter tubes, that is,

$$\left(\frac{\mathrm{d}p}{\mathrm{d}z}\right) = \left(\frac{\mathrm{d}p}{\mathrm{d}z}\right)_{\mathrm{Friedel}} \times \Omega_{\mathrm{Friedel}} \tag{14}$$

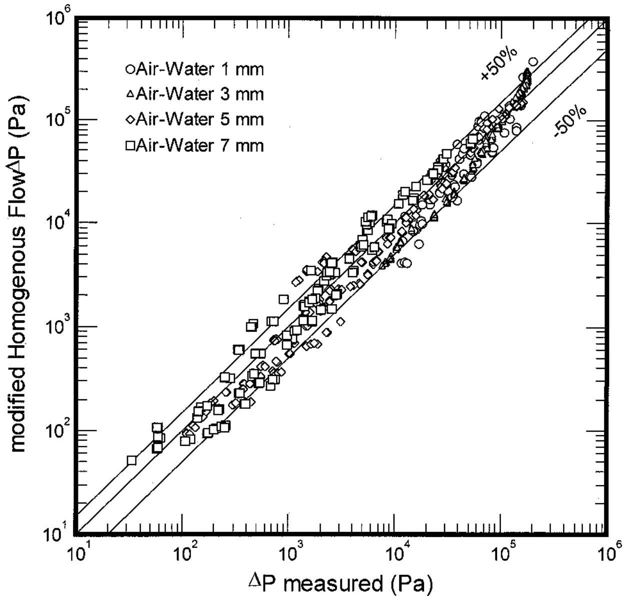

Fig. 7 Comparison of present data with the predictions by the modified homogeneous model.

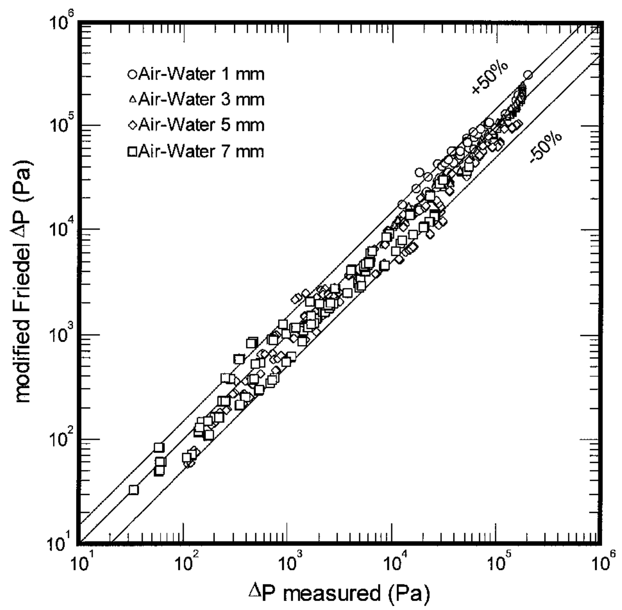

Fig. 8 Comparison of present data with the predictions by the modified Friedel correlation.[11]

$$\Omega_{\text{Friedel}} = \begin{cases} \dfrac{0.0333 \times Re_{L0}^{0.45}}{Re_G^{0.09}(1 + 0.4 \times e^{-Bo})} & \text{for} \quad Bo < 2.5 \\ \dfrac{We^{0.2}}{(2.5 + 0.06 \times Bo)} & \text{for} \quad Bo \geq 2.5 \end{cases} \quad (15)$$

where $Re_G = Gxd/\mu_G$, $Re_{L0} = Gd/\mu_L$, and $(dP/dz)_{\text{Friedel}}$ is the two-phase pressure gradient predicted by the Friedel correlation. Detailed comparison between Eq. (14) and all of the present air-water data is shown in Fig. 8. The mean deviation for the comparison in Fig. 8 is 19.88%.

To check the capabilities of the proposed correlations, the modified homogeneous model [Eq. (12)] and the modified Friedel correlation [Eq. (14)] were tested against available data from the literature (Figs. 9 and 10, respectively). The experiment data used in the comparisons in Figs. 9 and 10 are Hashizume's experimental data of 85 R-12 points and 122 R-22 points in a 10-mm-diam tube,[25] Shieh and Yang's 58 data of R-134a in 2- and 3-mm-diam tubes,[26] the Ungar et al.[14] data of R-12 in a 4.6-mm-diam tube at lunar gravity condition,[10] and the Chen et al. 252 data of R-410A in 3-, 5-, 7-, and 9-mm tubes.[24] The mean deviations for the comparison in Figs. 9 and 10 are 23.76 and 23.98%, respectively. Figure 11 is the comparison of Ungar and Cornwell's ammonia data[2] with the predictions made by the modified homogeneous model and the modified Friedel correlation: The mean deviations for the modified homogenous model and the modified Friedel correlation are 22.31 and 37.61%, respectively. Fairly good agreement of data and predictions is observed in Figs. 9–11. Note that the proposed modified homogeneous model and the Friedel correlation are only applicable for tube diameters less than 10 mm.

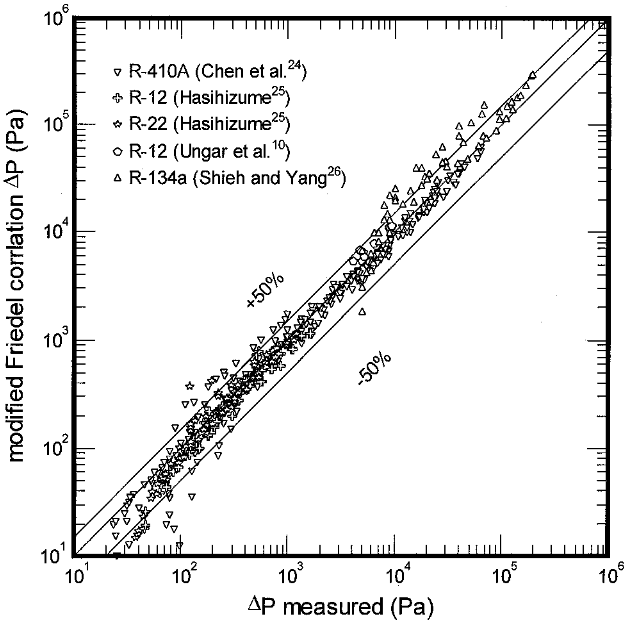

Fig. 9 Comparison of the refrigerant data with the predictions by the modified Friedel correlation.[11]

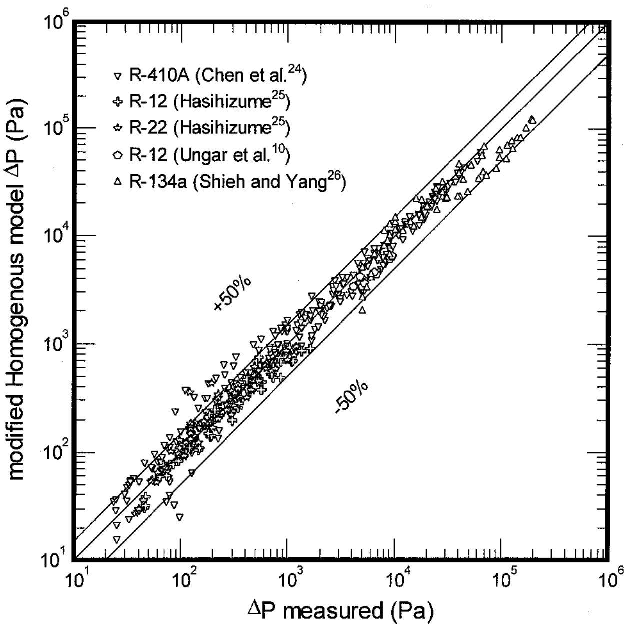

Fig. 10 Comparison of the refrigerant data with the predictions by the modified homogeneous model.

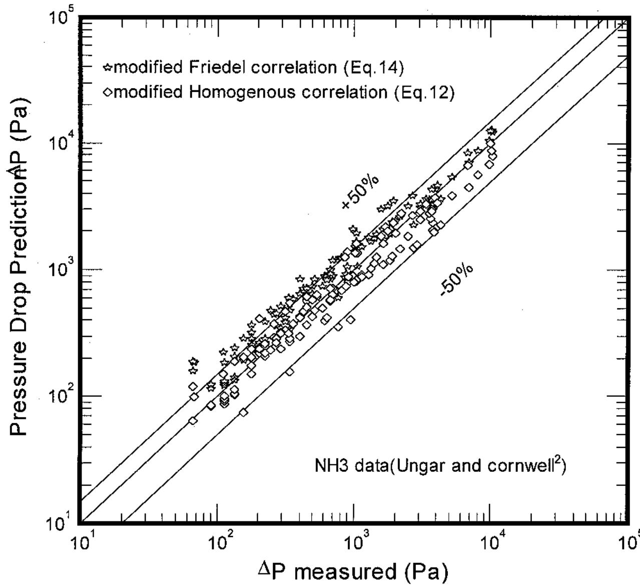

Fig. 11 Comparison of the ammonia data with the predictions by the modified homogeneous model and the modified Fridel correlation.[11]

Conclusions

In summary, frictional pressure drop for two-phase air–water was measured in small horizontal tubes with inside diameter in the range from 1.0 to 7.0 mm. The flow pattern was also observed in this test. Results of this study are summarized as follows:

1) The experimental results indicate that the empirical correlations widely used for large tubes could not predict the data with acceptable accuracy. The homogeneous model shows better predictive ability than other empirical correlations.

2) The bubble data and slug flow data are best predicted by the homogeneous flow model and the slug flow model with $Co = 1.2$, respectively.

3) The value of calculated interfacial friction factor ratio for annular flow data is obviously smaller than the normal size tubes because the surface tension tends to smooth the liquid–vapor interface in smaller tubes.

4) The predictions by the annular flow model with the correlated interfacial friction factor ratio give fairly good agreement with the annular flow data.

5) The modified correlations by introducing the Bond number and Weber number show good agreement with the present air–water data, as well as with five available data sets of ammonia and refrigerants from the literature.

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