PERGAMON International Journal of Multiphase Flow 27 (2001) 1293–1299

International Journal of Multiphase Flow

www.elsevier.com/locate/ijmulflow

Brief Communication

Two-phase pressure drop of air–water and R-410A in small horizontal tubes

Ing Youn Chen [a], Kai-Shing Yang [a], Yu-Juei Chang [b], Chi-Chung Wang [b,*]

[a] *Graduate School of Engineering Science and Technology, National Yunlin University of Science and Technology, 640 Taiwan, ROC*

[b] *Energy and Resources Laboratories Industrial Technology, Research Institute, Hsinchu, 310 Taiwan, ROC*

Received 6 February 2000; received in revised form 30 December 2000

1. Introduction

The calculation of pressure drop in any two-phase flow system is very important in the design of steam-power and petrochemical plants, refrigeration and air-conditioning systems. During recent years, the design of residential air conditioners has employed smaller diameter tube (6.35–9.53 mm) in order to improve the airside performance and to reduce the refrigerant charge into the system and more recently the air-conditioning manufacturers are implementing the related application by use of 4–5 mm diameter tubes. Knowledge of the two-phase frictional characteristics is essential since it would certainly improve the accuracy of the design of a thermal system. Unfortunately, most of the predictive correlations of pressure drop are based on the experimental data with tube diameter greater than 10 mm. Extrapolations of these correlations to applications utilizing the small diameter tubes are uncertain. It seems despite the important application of two-phase flow in small diameter tubes, the adequate frictional two-phase pressure drop correlations and the published experimental data for small tubes are very rare. Some of the relevant studies are summarized in the following.

Ungar and Cornwell (1992) 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). They found that the ammonia two-phase flow in small diameter tubes could not be predicted with acceptable accuracy using the correlations applicable for large tubes. Their ammonia pressure drop data were well described by the McAdams et al. (1942) homogeneous model. Triplett et al. (1999) conducted air–water two-phase experiments in 1.1 and 1.45 mm diameter tubes. Their pressure drop data of bubbly and

---

[*] Corresponding author. Present address: D400 ERL/ITRI Bldg. 64, 195–6 Section 4, Chung Hsing Road, Chutung, Hsinchu 310, Taiwan, ROC. Tel.: +886-3-5916294; fax: +886-3-5820250.

E-mail address: ccwang@itri.org.tw (C.-C. Wang).

PII: S0301-9322(01)00004-0

slug flow agree with the homogeneous model. For annular flow, the homogeneous flow model and other widely used correlations significantly over-predicted the frictional pressure drop.

In view of the previous investigations, the existing correlations may fail to describe the two-phase frictional characteristics of the small diameter tube. Hence it is an objective of the present study to provide more frictional data for tube diameters of 1–9 mm. Experiments were conducted in the air–water and R-410A systems. The air–water and R-410A fluids were chosen because of their diverse difference in properties. The overall goal of this study is to extend the applicability of the existing correlations in small diameter tubes by appropriate modification.

2. Background of pressure drop predictions by empirical correlations

Lockhart and Martinelli (1949) defined the two-phase frictional multipliers. Their data also indicated that the multipliers were a function of the Martinelli parameter alone. These multipliers are given by

$$\phi_{\mathrm{L}}^2 = \frac{\mathrm{d}P_{\mathrm{f}}/\mathrm{d}z}{\mathrm{d}P_{\mathrm{f,L}}/\mathrm{d}z}, \quad \phi_{\mathrm{G}}^2 = \frac{\mathrm{d}P_{\mathrm{f}}/\mathrm{d}z}{\mathrm{d}P_{\mathrm{f,G}}/\mathrm{d}z}, \tag{1}$$

where $\mathrm{d}P_{\mathrm{f}}/\mathrm{d}z$ is the measured two-phase frictional pressure gradient, and $\mathrm{d}P_{\mathrm{f,L}}/\mathrm{d}z$ and $\mathrm{d}P_{\mathrm{f,G}}/\mathrm{d}z$ 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

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

The relationship of ϕ_{L}^2 and ϕ_{G}^2 to X^2 was originally presented in graphical forms, but Chisholm (1967) had approximated these relationships by the simple expressions:

$$\phi_{\mathrm{L}}^2 = 1 + CX + X^2, \quad \phi_{\mathrm{L}}^2 = 1 + \frac{C}{X} + \frac{1}{X^2}. \tag{3}$$

Tabular constants for C are given by Chisholm, depending on whether the liquid and gas phases are laminar or turbulent flow.

Friedel (1979) proposed a correlation based on a bank of 25,000 data that is in terms of a multiplier by:

$$\phi_{\mathrm{LO}}^2 = \frac{\mathrm{d}P_{\mathrm{f}}/\mathrm{d}z}{\mathrm{d}P_{\mathrm{f,LO}}/\mathrm{d}z}, \tag{4}$$

where $\mathrm{d}P_{\mathrm{f,LO}}/\mathrm{d}z$ is the frictional pressure gradient for total flow assumed liquid. The Friedel correlation had been recommended by Whalley (1987) as an accurate correlation for the frictional two-phase pressure gradient when $(\mu_{\mathrm{L}}/\mu_{\mathrm{G}}) < 1000$. However, the Friedel correlation was found significantly over-predicted the data having smaller liquid mass flux and under-predicted the higher liquid mass flux data in capillary tubes (Triplett et al., 1999).

The homogeneous flow approximation treats the two-phase mixture as a single fluid with mixture properties (McAdams et al., 1942). Although the homogeneous flow model was developed for general use, it had been shown (Wallis, 1969) to be accurate only for bubbly flow. Recently, the homogeneous flow model was reported to give more accurate predictions in smaller tubes (Ungar and Cornwell, 1992; Triplett et al., 1999).

3. Experimental apparatus

The test apparatus is consisted of a R-410A loop and an air–water loop. Detailed description of the test facility can be found in Chang et al., 2000. The test tubes for air–water flow are round copper tubes having inner diameter (d) of 1.02, 3.17, 5.05 and 7.02 mm, and the corresponding pressure drop measured length are 150, 995, 995 and 995 mm, respectively. The tube diameters of the tested copper tubes for R-410A are 3.17, 5.05, 7.02 and 9 mm, and the corresponding tube length are all 700 mm. The quality of the air–water (x) ranged from 0.0001 to 0.9, while the quality of R-410A was from 0.1 to 0.9. The measured refrigerant mass flux (G) ranged from 50 to 600 kg/m^2 s for R-410A and from 50 to 3000 kg/m^2 s for the air–water mixtures. The accuracy of the flow meter for refrigerant, water and air is within ±0.2%, ±0.3% and ±0.5% of the test spans, respectively. The pressure drop of the air–water mixtures is measured by a precision differential pressure transducer, which has an adjustable span of 1300–13,000 Pa and its accuracy is ±0.3% of the measurements. The air and water temperatures were measured by resistance temperature device having a calibrated accuracy of 0.1 K.

The air–water tests were conducted in an ambient environment at 298 K, while the adiabatic two-phase R-410A tests were conducted at saturation temperatures of 298 and 278 K. Totally, there are 720 points of air–water data and 166 points of R-410A data obtained in this study.

4. Results and discussion

All the measured two-phase pressure drop data are compared with the predictions of empirical correlations of Chisholm (1967), Friedel (1979), and the homogeneous model. The mean deviations of the relevant correlations are 82.9%, 218.0% and 53.7%, respectively. Note that the average viscosity used in the homogeneous model is defined by Beatie and Whalley (1982). If the definition of McAdams et al. (1942) is used, the corresponding mean deviation is increased from 53.7% to 64.9%. Apparently, the predictive ability of the homogeneous model is superior to other correlations. The over-prediction of the homogeneous model is observed for the air–water data with smaller diameters of 1 and 3 mm at higher mass flux and higher quality region. Further, detectable under-predictions of the R-410A data for 3 and 5 mm diameter are seen in the higher mass flux and higher quality region. The trend of this result is analogous to the predicted results of the Friedel correlation.

This above-mentioned deviation may be related to the difference of the surface tension (or more specifically, wetting characteristics) between R-410A and water. Note that the surface tension of water at 298 K is 0.073 N/m, however, the surface tension of R-410A at 278 and 298 K are 0.008 and 0.005 N/m, respectively. As pointed out by Barajas and Panton (1993) who identified the existence of a special two-phase flow pattern called rivulet or multiple rivulet pattern in small diameter tubes, the rivulet flow pattern characterizes a stream of liquid (or multiple stream of liquid) flows on the tube surface. The stream generally does not flow straight down the tube length, but twisted its way down the tube length much like a river. For fluids having smaller contact angle (<34°, such as refrigerant R-410A), the rivulet and multiple rivulet flow pattern do not appear. The liquid will spread around the periphery and caused higher flow resistance. Conversely, for fluids having higher contact angle (such as water in the present case), the flow resistance are expected to be smaller. This phenomenon may become comparatively pronounced as the tube size is reduced. Hence, one can see the existing correlations may underestimate the pressure drops of R-410A and over-predict the results of water.

For two-phase flow in small tubes, the effect of surface tension force should be taken into account as compared to gravitational force. Ungar et al. (1998) indicated that the criterion to satisfy this balance is related to Bond number, where the Bond number is defined as

$$Bo = g(\rho_L - \rho_G)\frac{(d/2)^2}{\sigma}. \tag{5}$$

When the value of *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. To extend the applicability of the existing correlations to smaller tubes, the effects of surface tension (σ), tube diameter (d), and total mass flux (G) are included in the modification of pressure drop prediction. The homogeneous model is then modified with the inclusion of Bond number and Weber number ($We = G^2 d/\sigma\rho_m$), and other related significantly dimensionless parameters in order to develop a general correlation for practical application. The modified homogeneous model is given as:

$$\left(\frac{dp}{dz}\right) = \left(\frac{dp}{dz}\right)_{\text{hom}} \Omega_{\text{hom}}, \tag{6}$$

$$\Omega_{\text{hom}} = \begin{cases} 1 + (0.2 - 0.9\,e^{-Bo}) & \text{for } Bo < 2.5, \\ 1 + \left(We^{0.2}/e^{Bo^{0.3}}\right) - 0.9\,e^{-Bo} & \text{for } Bo \geqslant 2.5, \end{cases} \tag{7}$$

where $(dp/dz)_{\text{hom}}$ is the two-phase pressure gradient predicted by the homogeneous model by use of an average viscosity defined by Beatie and Whalley (1982). Fig. 1 presents the comparisons between the modified homogeneous prediction and the experimental data. The above-mentioned (Eqs. (6) and (7)) give a mean deviation of 30.9%

The Friedel correlation (1979) is the only correlation that intended to include the effect of surface tension (Weber number, inertia/surface tension) and gravity (Froude number, inertia/gravity). However, the exponents of the dependence of Weber number, 0.035, and Froude number, 0.045, are rather small. For small diameter tube, 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 overpredict the effect of gravity in small diameter tube. In this connection, a slight modification to the Friedel correlation is proposed that can provide better predictive ability of the Friedel correlation for smaller diameter tubes. i.e.,

$$\left(\frac{dp}{dz}\right) = \left(\frac{dp}{dz}\right)_{\text{Friedel}} \Omega, \tag{8}$$

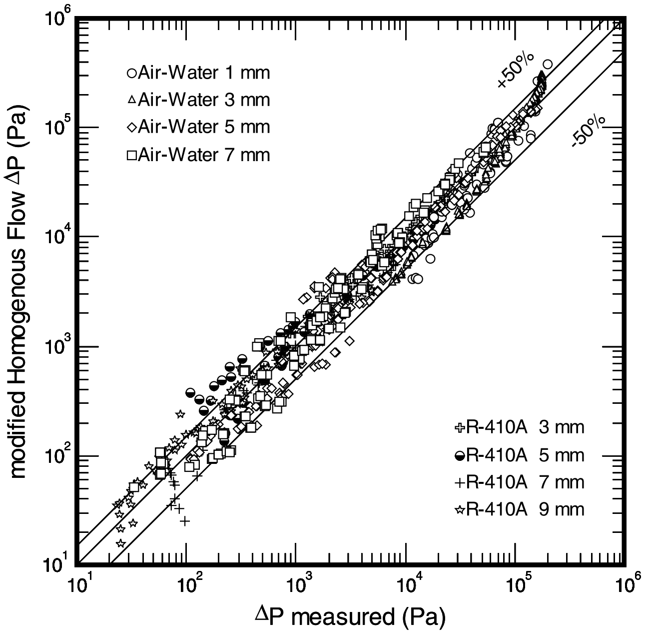

Fig. 1. Comparison between the measured pressure drop data and predictions by the modified homogeneous model.

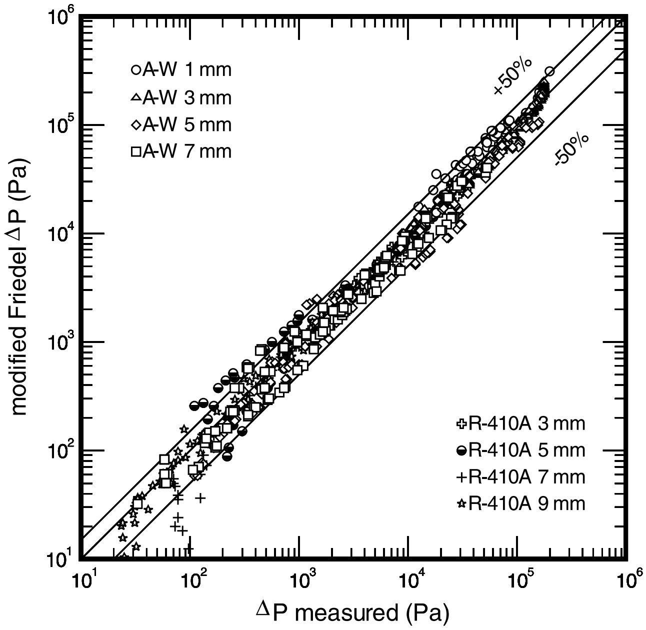

Fig. 2. Comparison between the measured pressure drop data and predictions by the modified Friedel correlation.

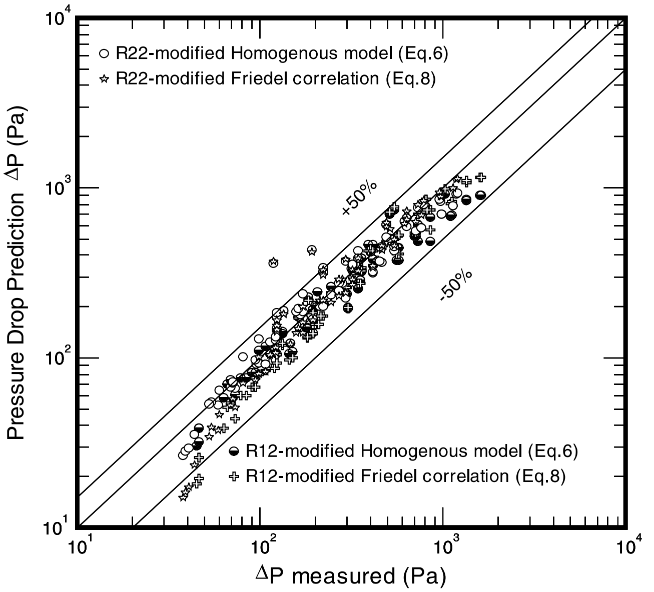

Fig. 3. Comparison of the proposed correlations with Hasihizume (1983).

$$\Omega = \begin{cases} \dfrac{0.0333 Re_{\mathrm{LO}}^{0.45}}{Re_{\mathrm{G}}^{0.09}(1 + 0.4\mathrm{e}^{-Bo})} & \text{for } Bo < 2.5, \\ \dfrac{We^{0.2}}{(2.5 + 0.06Bo)} & \text{for } Bo \geqslant 2.5, \end{cases} \tag{9}$$

where $Re_{\mathrm{G}} = Gxd/\mu_{\mathrm{G}}, Re_{\mathrm{LO}} = Gd/\mu_{\mathrm{L}}$ and $(\mathrm{d}p/\mathrm{d}z)_{\mathrm{Friedel}}$ is the two-phase pressure gradient predicted by the Friedel correlation. Detailed comparison of Eq. (8) against the test data is shown in Fig. 2. The mean deviation of Eq. (8) is 19.8%. It should be further pointed out that the proposed modification to the homogeneous model and the Friedel correlation are applicable for tube diameters less than 10 mm.

To check the capabilities of the proposed correlations, the modified homogeneous model (Eq. (6)) and the modified Friedel correlation (Eq. (8)) were tested against the data from the literature. However, the published frictional two-phase pressure drop data in small tubes are very rare. Furthermore, many of the published data did not include related details of the experimental conditions such as total mass flux, quality, and working pressure that makes their data hard to extractable. Hence, comparisons were made to those with specified conditions or tabulated data (Hasihizume, 1983). Fig. 3 is the comparisons with Hasihizume (1983) results of R-12 and R-22 in a 10 mm-diameter tube. Fairly good agreements of data and predictions are observed in the figure.

5. Concluding remarks

1. The Chisholm correlation and the Friedel correlation failed to predict the test data for smaller diameter tubes.

2. The homogeneous model shows better predictions than the other empirical correlations. However, at high quality and high mass flux region for smaller tubes, over-predictions of the air–water data and under-predictions of the R-410A data are observed. It is very likely that this phenomenon is related to the variety of surface tension in the working fluids (or wetting characteristics).
3. A slight modification to the homogeneous flow model is proposed that gives a mean deviation of 30.9%.
4. A correction to the Friedel correlation is proposed that can describe the present data set with a mean deviation of 19.8%.
5. Fairly good agreements are observed between the proposed correlations and test results of Hasihizume (1983).

Acknowledgements

The authors would like to acknowledge the financial supports provided by the Energy Commission of the Ministry of Economic Affairs, Taiwan, ROC and National Science Committee (NSC 89-2212-E-224-007)

References

Barajas, A.M., Panton, R.L., 1993. The effects of contact angle on two-phase flow in capillary tubes. Int. J. Multiphase flow 19, 337–346.

Beatie, D.R.H., Whalley, P.B., 1982. A simple two-phase frictional pressure drop calculation method. Int. J. Multiphase Flow 8, 83–87.

Chang, Y.J., Chiang, S.K., Chung, T.W., Wang, C.C., 2000. Two-phase frictional characteristics of R-410A and air–water in a 5-mm smooth tube. ASHRAE Trans. 106, 792–797.

Chisholm, D., 1967. A theoretical basis for the Lockhart–Martinelli correlation for two-phase flow. Int. J. Heat Mass Transfer 10, 1767–1778.

Friedel, L., 1979. Improved friction pressure drop correlations for horizontal and vertical two-phase pipe flow. Presented at the European Two-phase Group Meeting, Ispra, Italy, Paper E2.

Hasihizume, K., 1983. Flow pattern, void fraction and pressure drop refrigerant two-phase flow in a horizontal pipe – I. Int. J. Multiphase Flow 9, 399–410.

Lockhart, R.W., Martinelli, R.G., 1949. Proposed correlations for isothermal two-phase two-component flow in pipes. Chem. Eng. Prog. 45, 39–48.

McAdams, W.H., Woods, W.K., Heroman Jr., L.C., 1942. Vaporization inside horizontal tubes – II Benzene–oil mixtures. Trans. ASME 64, 193–200.

Triplett, K.A., Ghiaasiaan, S.M., Abdel-Khlik, S.I., LeMouel, A., Cord, B.N., 1999. Gas–liquid two-phase flow in microchannels. Part II: Void fraction and pressure drop. Int. J. Multiphase Flow 25, 395–410.

Ungar, E.K., Cornwell, J.D., 1992. Two-phase pressure drop of Ammonia in small diameter horizontal tubes. AIAA paper 92-3891.

Ungar, E.K., Chen, I.Y., Chan, S.H., 1998. Selection of a gravity insensitive ground fluid and test configuration to allow simulation of two-phase flow in microgravity. ASME Proceedings of the Seventh AIAA/ASME Joint Thermophysics and Heat Transfer Conference, HTD Vol. 357, pp. 71–77.

Wallis, G.B., 1969. One Dimensional Two-phase Flow. McGraw-Hill, New York, NY.

Whalley, P.B., 1987. Boiling, Condensation and Gas–Liquid Flow. Oxford University Press, New York.