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Technical Note

An empirical correlation for two-phase frictional performance in small diameter tubes

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Abstract

Experimental two-phase pressure drop data in small diameter tubes ($D < 10$ mm) have been collected and updated from the literature which contain eight refrigerant and three air–water datasets. Comparisons between the data and the predictions indicate that the Chisholm correlation fails to predict the data. The Friedel correlation and Souza and Pimenta's correlation give fair predictions for the refrigerant data, but fail to predict the air–water data due to the surface tension effect. The homogeneous model shows a better predictive ability (a mean deviation of 34.7%) than the other empirical correlations. In this regard, an empirical correlation based on the homogeneous model was developed. By introducing the Bond number and Weber number to the modified correlation, the new correlation gives a mean deviation of 19.1% based on 1484 data points.

Keywords: Two-phase flow; Pressure drop; Small diameter tube

1. Introduction

The calculation of the 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. Knowledge of the two-phase frictional characteristics is essential since it would certainly improve the accuracy of the design of a thermal system.

Most of the frequently used correlations to predict the two-phase frictional pressure gradient take the form of two-phase frictional multipliers. The concept for using the multipliers was first introduced by Lockhart and Martinelli [1]. In their formulation, the multipliers were a function of the Martinelli parameter alone. These multipliers are given by

$$\phi_L^2 = \frac{dP_f/dz}{dP_{f,L}/dz}, \quad \phi_G^2 = \frac{dP_f/dz}{dP_{f,G}/dz}, \tag{1}$$

where dP_f/dz is the measured two-phase frictional pressure gradient, and $dP_{f,L}/dz$ and $dP_{f,G}/dz$ 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

$$X^2 = \frac{dP_{f,L}/dz}{dP_{f,G}/dz}. \tag{2}$$

The relationship of ϕ_L^2 and ϕ_G^2 to X^2 was originally presented in graphical forms, but Chisholm [2] had approximated these relationships by the simple expressions:

$$\phi_G^2 = 1 + CX + X^2, \quad \phi_L^2 = 1 + \frac{C}{X} + \frac{1}{X^2}. \tag{3}$$

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

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Nomenclature

Bo	Bond number, $g(\rho_L - \rho_G)(D/2)^2/\sigma$
C	constant in Chisholm correlation
D	inside diameter of the tube (m)
f_m	homogeneous friction factor, defined in Eq. (9)
dP/dZ	measured two-phase pressure gradient (N m^{-3})
Fr	Froude number, $G^2/(gD\rho_m^2)$
g	gravitational acceleration (m s^{-2})
G	total mass flux (kg m^{-2} s^{-1})
P	pressure (N m^{-2})
Re_G	superficial gas Reynolds number, GxD/μ_G
Re_{LO}	liquid Reynolds number based on the total mass flux, GD/μ_L
Re_m	homogeneous Reynolds number, GD/μ_m
We	Weber number, $G^2D/(\rho_m\sigma)$
x	vapor quality
X	Martinelli parameter
z	tube axial direction (m)

Greek symbols

μ	dynamic viscosity (N 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^{-1})
ϕ_G^2	two-phase friction multiplier for gas flowing alone
ϕ_L^2	two-phase friction multiplier for liquid flowing alone
ϕ_{LO}^2	two-phase friction multiplier for total flow assumed liquid
Ω	homogeneous pressure drop correction factor defined in Eq. (7)

Subscripts

f	friction
G	gas phase only
L	liquid phase only
LO	for total flow assumed liquid phase

Friedel [3] proposed a correlation based on a bank of 25,000 data points that is in terms of a multiplier given by

$$\phi_{LO}^2 = \frac{dP_f/dz}{dP_{f,LO}/dz}, \tag{4}$$

where $dP_{f,LO}/dz$ is the frictional pressure gradient for the total flow assumed to be liquid. The Friedel correlation had been recommended by Whalley [4] as an accurate correlation for the frictional two-phase pressure gradient when $(\mu_L/\mu_G) < 1000$. However, the Friedel correlation was found to significantly over-predict the data having smaller liquid mass flux and to under-predict the data of higher liquid mass flux of air–water in capillary tubes (Triplett et al. [5], Wang et al. [6]). Interestingly, Yang et al. [7] found that the Friedel correlation gives fair prediction of the refrigerant data in a 3-mm diameter tube. In this regard, for small diameter tubes, Yang et al. [7] concluded that the applicability of the Friedel correlation might be more appropriate for those fluids having smaller surface tension such as refrigerants.

Souza and Pimenta [8] developed a specific correlation based on the results from refrigerants. Newell and Shah [9] had recommended their correlation for calculation of the two-phase frictional pressure drop of refrigerants. However, their predictive ability to those fluids having larger surface tension (e.g., water) is not known.

The homogeneous flow approximation treats the two-phase mixture as a single fluid with mixture properties (McAdams et al. [10]). Although the homogeneous flow model was developed for general use, this model would be valid for the bubbly flow (Collier and Thome [11]). Yet, the homogeneous flow model was reported to give comparatively accurate predictions in smaller tubes for various flow conditions (Ungar and Cornwell [12] and Triplett et al. [5]).

In summary, the existing correlations for predicting the two-phase frictional performance are mainly based on a database for larger diameter tubes. Extrapolations of these correlations to applications utilizing small diameter tubes are uncertain. The objective of this study is to develop an appropriate correlation to predict the two-phase pressure drop in small tubes, $D < 10$ mm, based on the relevant database.

2. Data base used to develop the correlation

An effort has been made to collect frictional two-phase pressure drop data from *air–water and* a wide variety of refrigerants. Data was collected only when the tube diameter is less than 10 mm. In Table 1, a complete list has been given and the relevant operation parameters are shown. The present data bank includes those from Reinarts et al. [13], Hasihizume [14], Zhang [15], Zhao and Rezkallah [16], Chen et al. [17], Wang et al. [18],

Table 1
Relevant details of the database

Reference	Reinarts et al. [13]	Hasihizume et al. [14]	Hasihizume et al. [14]	Zhang [15]	Zhang [15]	Wang et al. [18]	Wang et al. [18]	Wang et al. [18]	Yang et al. [7]	Yang et al. [7]	Chen et al. [17]	Zhao and Rezkallah [16]	Triplett et al. [5]
Data points	16	106	85	15	40	108	219	254	68	67	347	41	118
Working fluid	Ammonia	R-22	R-12	R-134a	R-404	R-22	R-407C	R410A	R-125	R-407C	Air–water	Air–water	Air–water
Tube diameter (mm)	3.34	10, 3.26	10	6.16	3.26, 2.13	4.98, 7.02	3, 4.98, 7.02, 9.02	3, 4.98, 7.02, 9.02	3.17	3.17	1.02, 3.17, 5.01, 7.07	9.53	1, 1.45
Pressure (kPa)	615	913–2060	564–1220	1020–1880	1270–3300	576–1040	657–1200	994–1690	896–1220	659–1050	102–407	97.6–1500	–
Mass flux G (kg/m^2 s)	125–284	88–1042	88–354	582–639	194–1025	94–408	50–655	50–638	306–1028	283–1038	45–3279	77–2483	23–6000
Quality x	0.17–0.7	0.08–0.9	0.08–0.81	0.2–0.85	0.17–0.88	0.08–0.9	0.08–0.91	0.08–0.91	0.088–0.9	0.094–0.91	0.01–0.93	0.005–0.26	0.0006–0.74

Yang et al. [7] and Triplett et al. [5]. Detailed information about the database is tabulated in Table 1.

For two-phase flow in small tubes, the influence of surface tension force is comparatively reinforced and should be taken into account as compared to gravitational force. Ungar et al. [19] indicated that the criterion to satisfy this balance is related to the Bond number, where the Bond number is defined as

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

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) should be incorporated into the prediction of the pressure drop. As mentioned previously, the homogeneous model was reported to have a better predictive ability than the other empirical correlations. Therefore, the homogeneous model is then modified with the inclusion of Bond number and Weber number ($We = G^2D/\sigma\rho_m$) and other related dimensionless parameters in order to develop a general correlation for practical application. The proposed modified homogeneous model is given as

$$\left(\frac{dP}{dz}\right) = \left(\frac{dP}{dz}\right)_{hom} \times \Omega, \quad (6)$$

$$\Omega = \frac{0.85 - 0.082Bo^{-0.5}}{0.57 + 0.004Re_G^{0.5} + 0.04Fr^{-1}} + \frac{80We^{-1.6} + 1.76Fr^{0.068} + \ln(Re_G) - 3.34}{1 + e^{(8.5-1000\rho_G/\rho_L)}}, \quad (7)$$

where

$$\left(\frac{dP}{dz}\right)_{hom} = \frac{4f_m}{D}\frac{G^2}{2\rho_m}, \quad (8)$$

$$f_m = \begin{cases} \frac{16}{Re_m} & \text{for laminar flow,} \\ 0.0791Re_m^{-0.25} & \text{for turbulent flow,} \end{cases} \quad (9)$$

where $Re_G = GD/\mu_G$, $Fr = G^2/gD\rho_m$ is the Froude number, and $(dP/dz)_{hom}$ is the two-phase pressure gradient predicted by the homogeneous model by use of an average viscosity defined by Beatie and Whalley [20]. Notice that the development of Eq. (7) is made by trail-and-error procedures. Firstly, the relevant influence of dimensionless parameters (Fr, Bo, Re_G, We, and ρ_G/ρ_L) and their interactions are examined. Then a selection of the appropriate form is carried out based on the minimum mean deviation criterion.

3. Results and discussion

Fig. 1 presents the comparisons between the predictions of the proposed modified homogeneous model and the experimental data. The above-mentioned equations (Eqs. (6) and (7)) give a mean deviation of 19.1%. All the collected two-phase pressure drop data sets are also compared with the predictions of the homogeneous model and the empirical correlations of Chisholm [2], Friedel [3] and Souza and Pimenta [8]. As shown in Table 2, the mean deviations of the relevant correlations are 34.7%, 95.1%, 80.4% and 66.9%, respectively. The comparisons between the data and the predictions indicate that the Chisholm correlation fails to predict the data. The Friedel correlation [3] and Souza and Pimenta's correlation [8] give fair predictions of the refrigerant data. The results are analogous to those reported by Yang et al. [7] and Newell and Shah [9], respectively. However, both the Friedel correlation [3] and Souza and Pimenta's correlation [8] fail to predict the air–water data due to the surface tension effect. This is because Souza and Pimenta's correlation [8] does not include the effect of surface tension whereas the Friedel correlation has a small exponent on the Weber bumber, 0.035l. A large deviation may be induced due to the significant difference of the surface tension between refrigerants and water. When compared to the predictive ability of the empirical correlations by Chisholm [2], Friedel [3] and Souza and Pimenta [8], the homogeneous model shows comparatively better predictive ability for the referred refrigerant and air–water data sets. Though the predictive ability of the proposed correlation outperforms the above-mentioned correlations, it should be further emphasized that the proposed correlation is applicable for $D < 10$ mm.

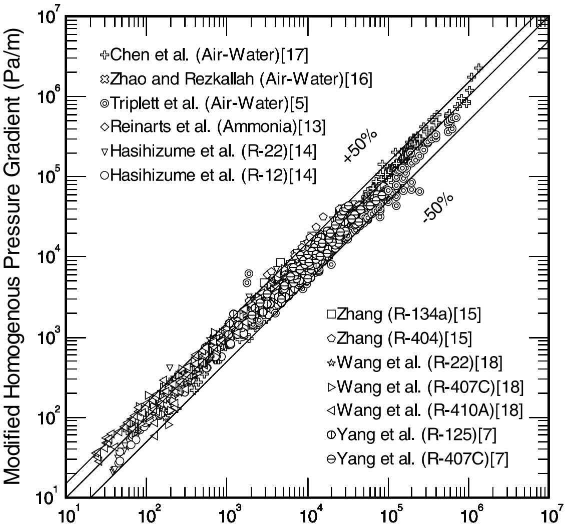

Fig. 1. Comparisons between the referred data and predictions by the modified homogeneous model.

Table 2
Comparisons of the mean deviation with the data source (in %)

Data source	Reinarts et al. [13]	Hasihizume et al. [14]	Zhang [15]	Wang et al. [18]	Yang et al. [7]	Chen et al. [17]	Zhao and Rezkallah [16]	Triplett et al. [5]	Overall deviation
Homogeneous [1]	35.83	22.13	32.19	32.98	28.18	53.61	14.77	23.86	34.7
Chisholm [2]	66.74	155.43	150.64	93.84	118.03	76.05	26.38	34.23	95.1
Friedel [3]	23.09	44.49	27.38	39.22	44.42	134.09	44.88	269.71	80.4
Souza and Pimenta [8]	17.93	19.08	26.70	26.40	24.33	169.25	74.36	113.87	66.9
Proposed correlation in his study	25.08	16.47	36.44	14.66	23.45	16.90	27.17	35.90	19.1

4. Conclusions

This study presents an empirical correlation of two-phase frictional performance based on eight data sets. The proposed correlation is applicable for small diameter tube ($D < 10$ mm). Comparisons are made between commonly used correlations and the collected data. Major conclusions of this study are summarized as follows:

1. The Chisholm correlation shows poor predictive ability to the referred data having smaller diameter tubes.
2. The Friedel correlation and the Souza and Pimenta's correlation give fair predictions for the refrigerant data, but fail to predict the air–water data.
3. The homogeneous model gives good predictions for the refrigerant and air–water data sets with a mean deviation of 34.7%, and shows a better predictive ability than the above empirical correlations.
4. A new correlation is proposed with the modification to the homogeneous flow model that gives a mean deviation of 19.1% from 1484 data points of eight refrigerant and three air–water data sets.

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