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Frictional pressure drop analysis for horizontal and vertical air-water two-phase flows in different pipe sizes

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ABSTRACT

This study performs an experimental investigation of frictional pressure drop in air–water two-phase flows in straight pipes. A reliable experimental database for the two-phase pressure drop and void fraction is established with a differential pressure transducer and a four-sensor conductivity probe, respectively. The two-phase flow investigated focuses on gas-dispersed flow regimes in different pipe diameters of 38.1 mm, 50.8 mm, and 101.6 mm. Systematic study on the effects of flow orientation, flow regime and pipe size is performed. The most commonly used predictive models for the two-phase frictional pressure drop are evaluated with the newly established database and the existing databases found in the literature. It is demonstrated that both the conventional Lockhart-Martinelli approach and the $\phi_f - <\alpha>$ correlation can generally predict the two-phase frictional pressure drop very well with different suggested values of coefficients C and n for different flow orientations, based on the established data. Meanwhile, the results show that the values of C and n are independent of the pipe size and the flow regime. The homogeneous flow model is evaluated with four β (ratio of volumetric flow rates) based mixture viscosity correlations. The predictions with the Beattie and Whalley mixture viscosity correlation are found to be the best regardless of the flow orientation. The Lockhart-Martinelli approach with the coefficient C calculated by correlation employed in the nuclear system analysis code RELAP5-3D and the Müller-Steinhagen and Heck correlation are also evaluated. It is found that these two modeling approaches as well as the homogeneous flow model tend to underestimate most of the experimental data. Improvements for pressure drop prediction in nuclear reactor safety analysis codes are observed.

1. Introduction

Multiphase flows have become increasingly important in a wide variety of science and engineering systems such as power, heat transfer, and transport systems. For optimum design and safe operations, it is necessary to determine the pressure drop in these systems. The pressure gradient in two-phase flows can be derived from the momentum equation. The rate of change in the static pressure in a channel is the summation of three components:

$$\left(\frac{dp}{dz}\right)_{2\phi} = \left(\frac{dp}{dz}\right)_{fric,2\phi} + \left(\frac{dp}{dz}\right)_{grav,2\phi} + \left(\frac{dp}{dz}\right)_{acc,2\phi} \quad (1)$$

where $(dp/dz)_{fric,2\phi}$ is the pressure gradient due to the friction at pipe wall and liquid-gas interface; $(dp/dz)_{grav,2\phi}$ is the pressure gradient due to gravity as a result of pipe elevation, and can be calculated by:

$$\left(\frac{dp}{dz}\right)_{grav,2\phi} = \rho_m g \sin\theta \quad (2)$$

where the two-phase mixture density (ρ_m) can be calculated by:

$$\rho_m = \alpha\rho_g + (1-\alpha)\rho_f \quad (3)$$

$(dp/dz)_{acc,2\phi}$ is the pressure gradient due to the expansion or contraction of gas phase as the two-phase mixture travels along the test section and can be calculated by:

$$\left(\frac{dp}{dz}\right)_{acc,2\phi} = \frac{d}{dz}\left[\frac{G_f^2}{\rho_f(1-\alpha)} + \frac{G_g^2}{\rho_g\alpha}\right] \quad (4)$$

This term was usually neglected in previous studies for non-boiling two-phase flows, such as air-water two-phase flows, since it offers a negligible contribution to the total pressure gradient. For the above

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Nomenclature

A	pipe cross-sectional area [m^2]
C	Chisholm parameter [–]
D	pipe inner-diameter [m]
f	Fanning friction factor [–]
g	gravitational acceleration [m/s^2]
G	mass flux [kg/m^2s]
j	superficial velocity [m/s]
L	length [m]
n	exponent in the $\phi_f - <\alpha>$ correlation [–]
Re	Reynolds number [–]

Greek symbols

α	void fraction [–]
β	ratio of volumetric flow rates [–]
θ	inclination angle [rad]
ρ	density [kg/m^3]
ϕ^2	two-phase frictional multiplier [–]
μ	dynamic viscosity [Nm/s^2]
σ	surface tension [N/m]
χ	mass quality [–]
X	Martinelli parameter [–]

Mathematical symbols

$< >$	area-average

Subscripts

2ϕ	two-phase
acc	acceleration
atm	atmospheric pressure condition
exp	experimental value
f	liquid phase
fo	liquid phase only (total mass flow rate reserved)
fric	friction
g	gas phase
go	gas phase only (total mass flow rate reserved)
grav	gravitation
loc	axial location of interest
m	mixture
pred	predicted value

equations, L, θ, α, G and ρ denote the pipe length, pipe inclination, void fraction, mass flux and density, respectively. The sub-scripts 2ϕ, f, g, and m denote the two-phase, liquid phase, gas phase and two-phase mixture, respectively.

Among these three components, the pressure gradient due to the friction in two-phase flows is the most complex and difficult one to predict due to its dependency on pipe inclination, flow regime, and pipe roughness. Over the past several decades, the two-phase frictional pressure drop has been investigated extensively by previous researchers. A summary of the literature review on the existing studies is given in Table 1. However, it is found that most of the previous work focused on studying the pressure drop in small diameter pipes (ID < 10 mm) as shown in the table. It is surprising to note that very limited studies have been performed in moderate (10 mm < ID < 100 mm), and large diameter pipes (ID > 100 mm), despite their wide applications in engineering systems. Meanwhile, there has been no consistent predicting approach for two-phase frictional pressure drop in different pipe sizes and flow orientations. Different approaches for the prediction of the two-phase frictional pressure drop are suggested by different researchers. Systematic studies on the effects of flow orientation, flow regime and pipe size on frictional pressure drop analysis are not available in previous research. In addition, among the existing studies in moderate and large diameter pipes, it is found that the average disagreement between measured and predicted pressure drop using previous models can easily exceed ± 20% (Ferguson and Spedding, 1995; Hamad et al., 2017). While the analysis on frictional pressure drop requires reliable experimental databases established based on strict experimental controls (e.g. accurate measurement of differential pressure, fluid flow rate, fluid temperature, etc.), the experimental data in previous analyses were still not abundant, which might cause the observed inconsistences. Also, accurate measurement of area-averaged void fraction is critical, which is required for the evaluation of the pressure drop due to gravity and acceleration, as shown in Eqs. (3) and (4). While these items are either zero or negligible in horizontal two-phase flows, they have significant contributions in vertical two-phase flows.

In an attempt to improve the accuracy and reliability in the prediction of two-phase frictional pressure drop, the current study first establishes a reliable experimental database for adiabatic air-water two-phase flows in straight smooth pipes with moderate and large inner diameters (38 mm < ID < 102 mm). Then, the database is used to investigate the effects of pipe size, flow regime, and flow orientation on frictional pressure drop analysis. The best modeling approaches for the prediction of frictional pressure drop for different flow orientations are suggested. Considering that the general approach to predict two-phase frictional pressure gradient is to find either a two-phase friction factor (homogeneous flow model), or a two-phase friction multiplier (separated flow model), these two types of approaches are reviewed first.

2. Existing two-phase frictional pressure drop modeling approaches

2.1. Homogeneous flow model

In the homogeneous flow model (HFM), the slip ratio is assumed to be one. Therefore, the gas and liquid phases have the same velocity as a two-phase mixture. In this case, the two-phase flow can be considered as a pseudo single-phase mixture during the calculation of the frictional pressure drop. Similar to a single-phase flow, the frictional pressure gradient can be expressed as a function of the mixture properties in the homogeneous flow model:

$$\left(\frac{dp}{dz}\right)_{fric,2\phi} = 2f_m\frac{G_m^2}{\rho_m D} \quad (5)$$

where the homogeneous mixture density can be calculated by Eq. (3). The Fanning friction factor of the two-phase mixture (f_m) is related to the mixture Reynolds number (Re_m) through the Blasius relation for turbulent flows by:

$$f_m = 0.079Re_m^{-0.25} \quad (6)$$

$$Re_m = \frac{G_m D}{\mu_m} \quad (7)$$

Here, the modeling of mixture viscosity (μ_m) has been studied by many researchers, and numerous correlations have been developed. As the present study focuses on air-water two-phase flows under atmospheric pressure, the mass quality is very small ($1.6\times10^{-5} < \chi < 3.4\times10^{-3}$) for the current test conditions. Therefore, calculating the μ_m using correlations based on the mass quality may not be accurate. Instead, the correlations to calculate the mixture viscosity (μ_m) as a function of the ratio of volumetric flow rates ($\beta = <j_g>/<j>$) are considered in the current study: