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Drift-flux correlation for gas-liquid two-phase flow in a horizontal pipe

Somboon Rassame[a,*], Takashi Hibiki[b]

[a] Department of Nuclear Engineering, Faculty of Engineering, Chulalongkorn University, Wangmai, Patumwan, Bangkok 10330, Thailand
[b] School of Nuclear Engineering, Purdue University, 400 Central Drive, West Lafayette, IN 47907-2017, USA

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ABSTRACT

A drift-flux correlation has been often used to predict void fraction of gas-liquid two-phase flow in a horizontal channel due to its simplicity and practicality. The drift-flux correlation includes two important drift-flux parameters, namely, the distribution parameter and void-fraction-weighted-mean drift velocity. In this study, an extensive literature survey for horizontal two-phase flow is conducted to establish void fraction database and to acquire existing drift-flux correlations. A total of 566 data is collected from 12 data sources and 4 flow-regime-dependent and 1 flow-regime-independent drift-flux correlations are identified. The predictive capability of the existing drift-flux correlations is assessed using the collected data. It is pointed out that the drift velocity determined by a regression analysis may include a significant error due to a compensation error between distribution parameter and drift velocity. In this study, a simple flow-regime-independent drift-flux correlation is developed. In the modeling approach, the void-fraction-weighted mean drift velocity is approximated to be 0 m/s, whereas the distribution parameter is given as a simple function of the ratio of non-dimensional superficial gas velocity to non-dimensional mixture volumetric flux. The newly developed correlation shows an excellent predictive capability of void fraction for horizontal two-phase flow. Mean absolute error (or bias), standard deviation (random error), mean relative deviation and mean absolute relative deviation of the correlation are 0.0487, 0.0985, 0.0758 and 0.206, respectively. The prediction accuracy of the correlation is similar to the correlation of Chexal et al. (1991), which was formulated based on the drift-flux parameters by means of many cascading constitutive relationships with numerous empirical parameters.

1. Introduction

The gas-liquid two-phase flow in a horizontal channel is often encountered in apparatuses, plants and pipelines in various industries such as chemical, petroleum, and nuclear industries. The void fraction is one of most important parameters to characterize horizontal gas-liquid two-phase flows and is a critical parameter for the design of industrial systems. A correlation based on the drift-flux model proposed by Zuber and Findlay (1965) has been used to predict void fraction in horizontal gas-liquid two-phase flows due to its simplicity and practicality. The drift-flux correlation includes two-important drift-flux parameters such as the distribution parameter characterizing the phase distribution and the void-fraction-weighted mean drift velocity characterizing the relative velocity between phases. These drift-flux parameters should be given by either a phenomenological model or an empirical correlation.

Franca and Lahey (1992) proposed a drift-flux correlation for horizontal gas-liquid two-phase flows. The distribution parameter is given by a constant value depending on the flow regime such as plug, slug, wavy-stratified and annular flow regimes. Lamari (2001) developed a similar drift-flux correlation for those four flow regimes with different sets of the drift-flux parameters. Silva et al. (2011) proposed a drift-flux correlation for intermittent flow regime, while Kong and Kim (2017) developed a drift-flux correlation for dispersed bubble flow regime. Although the drift-flux correlations mentioned above are flow-regime-dependent correlations, they provide the insight on how the flow regime affects the drift-flux parameters. However, most of the existing empirical drift-flux correlations were developed based on the researchers' own data or a limited number of collected data, and the applicability of the correlations to a wide range of flow conditions has not been well-examined.

For the purpose of implementing a drift-flux correlation into one-dimensional thermal-hydraulic system analysis code such as RELAP5 (Information Systems Laboratories, inc., 2001), Chexal et al. (1991) developed a flow-regime-independent drift-flux correlation applicable for a whole range of void fraction. Chexal et al. (1991) adopted an approach to formulate the drift-flux parameters by means of many cascading constitutive relationships with numerous empirical

* Corresponding author.
E-mail address: somboon.ra@chula.ac.th (S. Rassame).

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Nomenclature

A	Flow area [m^2]
C_0	Distribution parameter [-]
C_∞	Asymptotic value of distribution parameter [-]
D	Diameter [m]
D_H	Hydraulic equivalent diameter [m]
g	Gravitational acceleration [m/s^2]
j	Superficial velocity [m/s]
m_d	Mean absolute error [-]
m_{rel}	Mean relative deviation [-]
$m_{rel,\ ab}$	Mean absolute relative deviation [-]
N	Number of samples [-]
Re	Reynolds number [-]
s_d	Standard deviation [-]
v_{gj}	Drift velocity [m/s]

Greek symbols

α	Void fraction [-]
$\Delta\rho$	Density difference between phases [kg/m^3]
μ	Viscosity [Pa•s]
ρ	Density [kg/m^3]
σ	Surface tension [N/m]

Subscripts

cal.	Calculated value
exp.	Experimental value
f	Liquid phase
g	Gas phase

Superscripts

+	Non-dimensional quantity

Mathematical symbols

< >	Area averaged properties
<< >>	Void-weight area-averaged properties

parameters, and sacrificed a physics principle characterizing the drift-flux parameters in exchange for developing the flow-regime-independent drift-flux correlation. The drift-flux correlation proposed by Chexal et al. (1991) may be considered a kind of regression curve to reproduce the void fraction data.

As reviewed above, most of the flow-regime-dependent drift-flux correlations adopt a flow-regime-dependent constant value for the distribution parameter, which implies that the recommended distribution parameter may not include the effects of physical properties and flow kinematics on the distribution parameter. The flow-regime-independent correlation may not provide a clear understanding of dependent parameters on the drift-flux parameters. In view of these, this study revisits the development of a drift-flux correlation for horizontal gas-liquid two-phase flows with extensive data sets collected in a wide range of flow conditions. The predictive capability of the newly developed drift-flux correlation is compared with that of the correlation developed by Chexal et al. (1991).

2. One-dimensional drift-flux model formulation and existing drift-flux correlations for horizontal two-phase flow

2.1. One-dimensional formulation of drift-flux model

Zuber and Findley (1965) introduced a concept of “drift velocity” to take into account the velocity difference between two phases. Local drift velocity, v_{gj}, is defined as the difference between gas velocity, v_g, and mixture volumetric flux, j, as:

$$v_{gj} = v_g - j \tag{1}$$

Averaging Eq. (1) over a flow channel yields one-dimensional drift-flux model as:

$$\langle\langle v_g\rangle\rangle = C_0\langle j\rangle + \langle\langle v_{gj}\rangle\rangle \tag{2}$$

where $\langle\langle\rangle\rangle$ and $\langle\rangle$ are the void-fraction-weighted mean quantity and cross-sectional area-averaged quantity over the flow channel, respectively. The void-fraction-weighted mean gas velocity (hereafter, gas velocity for simplicity), $\langle\langle v_g\rangle\rangle$, distribution parameter and void-fraction-weighted mean drift velocity (hereafter, drift velocity for simplicity), $\langle\langle v_{gj}\rangle\rangle$, are defined as Eqs. (3)–(5), respectively.

$$\langle\langle v_g\rangle\rangle = \frac{\langle j_g\rangle}{\langle\alpha\rangle} \tag{3}$$

$$\langle\langle v_{gj}\rangle\rangle = \frac{\langle\alpha v_{gj}\rangle}{\langle\alpha\rangle} \tag{4}$$

$$C_0 = \frac{\langle\alpha j\rangle}{\langle\alpha\rangle\langle j\rangle} \tag{5}$$

where j_g and α are the superficial gas velocity and void fraction, respectively.

The distribution parameter and drift velocity can be, respectively, obtained by Eqs. (5) and (4) if the distributions of local void fraction and gas and liquid velocities are measured (Hibiki and Ishii, 2002). However, these distributions are often not available. Zuber and Findlay (1965) proposed an alternative method to determine the distribution parameter and drift velocity. If a linear relationship between $\langle j\rangle$ and $\langle\langle v_g\rangle\rangle$ exists in a test condition, the distribution parameter and drift velocity can be obtained as the slope and intercept in the drift-flux plot of $\langle j\rangle$ and $\langle\langle v_g\rangle\rangle$, respectively. However, a “compensation error” is common in this approach when the distribution parameter and drift velocity are determined. The uncertainty of one parameter (for example, distribution parameter) directly affects the value of another parameter (for example, drift velocity). If data are taken at high mixture volumetric flux conditions, it is difficult to determine the drift velocity accurately with a drift-flux plot. Therefore, some efforts to model the drift velocity based on drag law have been made to develop a constitutive equation for predicting the drift velocity (Ishii, 1977; Hibiki and Ishii, 2003).

The approximation of the linear relationship between $\langle j\rangle$ and $\langle\langle v_g\rangle\rangle$ is found to be reasonable in some test conditions such as vertical slug and churn flows in confined channels (Mishima and Hibiki, 1996; Ishii, 1977; Ozaki and Hibiki, 2015). However, it is pointed out that the approximation may not work for some test conditions such as two-phase flows in large size channels at low flow conditions (Hibiki and Ishii, 2003; Clark et al., 2014), subcooled boiling flows (Ishii, 1977; Hibiki et al., 2003; Brooks et al., 2012) and bubbly flows (Hibiki and Ishii, 2002). Ishii and Hibiki (2010) provided a brief review of existing constitutive equations for distribution parameter and drift velocity in various flow channels.

2.2. Existing drift-flux correlations for horizontal gas-liquid two-phase flows

In this section, some existing drift-flux correlations developed for horizontal gas-liquid two-phase flows will be reviewed briefly. The summary of the reviewed correlations is tabulated in Table 1.

Chexal et al. (1991) developed a flow-regime-independent drift-flux