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Drift-flux correlation for rod bundle geometries

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ABSTRACT

A new drift-flux correlation has been developed to predict void fraction over a wide range of two-phase flow conditions in rod bundle geometries. An experimental database that represents low liquid flow and low pressure conditions in a scaled 8 × 8 rod bundle test facility is emphasized for this work. At these conditions, recirculating flow patterns may affect two-phase flow characteristics. Such effects may not be appropriately considered in earlier rod bundle correlations for drift velocity and distribution parameter. In the current approach, an existing drift-flux correlation that accounts for the effect of recirculating flow as two-phase flow regimes transition from bubbly to cap-bubbly flow is incorporated to determine distribution parameter. A performance analysis demonstrates that the proposed correlation improves upon existing correlations with an average relative error of ±4.5% when predicting the database utilized for in this work. The new correlation is also demonstrated to scale appropriately to prototypic plant conditions.

1. Introduction

In order to simulate two-phase flow systems, extensive work has been dedicated towards developing the two-fluid and drift-flux models (Ishii and Hibiki, 2011). The drift-flux model utilizes mixture balance equations for mass, momentum, and energy along with an additional gas continuity equation. The two-fluid model incorporates a separate mass, momentum, and energy balance equation for each phase. Therefore, the drift-flux model is more practical for analyzing the overall response of a two-phase flow system when the phases are strongly coupled. That is, when the phases are near mechanical and thermal equilibrium. An important component of the one-dimension drift-flux model is a kinematic constitutive relation by Zuber and Findlay (1965). This relation considers the relative velocity of the dispersed and continuous phases. This kinematic constitutive relation is necessary because the drift-flux model incorporates a mixture momentum balance rather than a separate momentum balance for each phase as in the case of the two-fluid model. The important components of the kinematic constitutive relation are the drift velocity and distribution parameter. Accordingly, the accurate calculation of these drift-flux terms is important for the drift-flux model to appropriately represent two-phase flow systems.

Correlations for drift velocity and distribution parameter have been thoroughly investigated for a variety of system conditions. Kataoka and Ishii (1987) investigated stagnant liquid two-phase flow in large channels. Hibiki and Ishii (2002) developed a correlation for bubbly flow based on lateral bubble movement characteristics. Furthermore, they validated the existing drift velocity correlation by Ishii (1977) for bubbly flow conditions. A drift-flux correlation for internally heated annulus conditions has been developed analytically using a bubble layer thickness model (Hibiki et al., 2003). Goda et al. (2003) developed a distribution parameter correlation for downward flow. Hibiki and Ishii (2003) considered the effects of recirculating flow patterns when developing a correlation for forced convective two-phase flow in large flow channels. Hibiki et al. (2006) developed a drift-flux correlation at reduced gravity conditions for the different flow regimes. Julia et al. (2009) analytically derived a distribution parameter in a rod bundle sub-channel geometry. In the derivation, the difference between pipe and subchannel geometries was taken into account using the bubble layer thickness model (Hibiki et al., 2003). Chen et al. (2012a, 2012b) developed a correlation for stagnant liquid flow conditions in a rod bundle geometry. Ozaki et al. (2013)

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Nomenclature

C_0	distribution parameter (–)
C_∞	asymptotic value of distribution parameter (–)
D_H	hydraulic diameter (m)
D_0	rod diameter (m)
g	gravitational acceleration (m/s^2)
j	mixture volumetric flux (m/s)
j_f	superficial gas velocity (m/s)
j_f	superficial liquid velocity (m/s)
$N_{\mu f}$	Viscosity number (–)
V_{gj}	drift velocity (m/s)

Greek symbols

α	void fraction (–)
$\Delta\rho$	density difference (ρ_f - ρ_g) (kg/m^3)
ρ	density (kg/m^3)
σ	surface tension (N/m)
μ	viscosity (Pa s)

Subscripts

calc	calculated value
exp	experimentally measured value
g	gas phase
f	liquid phase
B	bubbly flow
P	pool flow (stagnant liquid)

Superscripts

+	non-dimensional

Mathematical symbols

$\langle\rangle$	area-averaged parameter
$\langle\langle\rangle\rangle$	void weighted mean parameter

Acronyms

BWR	boiling water reactor
PWR	pressurized water reactor

developed a drift-flux correlation using an 8 × 8 rod bundle at prototypic conditions.

The present work focuses on low pressure and low liquid flow conditions in a rod bundle geometry. Here, two characteristic length scales to consider are the subchannel hydraulic diameter and rod bundle case width. Similar global flow patterns observed in large diameter channels may occur in rod bundles because the case width and flow area are generally representative of a large flow channel. For instance, at low pressure and low liquid flow conditions, larger concentrations of void have been measured at the central (higher velocity) regions of large diameter channels during upward vertical two-phase flow (Ohnuki and Akimoto, 1996). Simultaneously, downward flow at the outer perimeter is measured (Ohnuki et al., 1995). These characteristics are attributable to recirculating flow patterns. Low pressure and low liquid flow systems may allow for recirculating flow patterns to form because of increased gravitational (buoyancy) forces and decrease liquid convective forces. Increased concentrations of void have also been observed in the central regions of a rod bundle at low pressure and low flow conditions (Paranjape et al., 2010). Considering the above observations in large diameter channels and the geometric similarities between large channels and rod bundles, recirculating flow patterns may also be relevant in rod bundles at low pressure and low liquid flow conditions. Even though the typical conditions of a nuclear power plant are considerably high in pressure and liquid flow rate, low pressure and low liquid flow conditions are important to consider. For instance, a variety of plant designs utilize passive safety systems. Two-phase flow during the actuation of such systems may be characterized by low pressure and low liquid flow. Advanced modular reactors may even utilize natural circulation during operating conditions. Previous rod bundle correlations that are formulated with respect to higher pressure and higher flow rates may not appropriately represent these instances.

The objective of the present work is to develop a new drift-flux correlation that appropriately considers two-phase flow mechanisms that occur at low pressure and low liquid flow conditions. Furthermore, it is important that the new correlation scales appropriately to a wide range of pressure conditions and flow rates. In terms of flow regime, the proposed correlation may be applicable to bubbly, cap-bubbly, and churn-turbulent flow. Following the development of the proposed correlation, a performance analysis is conducted for comparison against earlier correlations and available databases.

2. The drift-flux approach

2.1. The kinematic constitutive relation of the drift-flux model

The kinematic constitutive relation by Zuber and Findlay (1965) for the drift-flux model can be used to calculate void fraction in two-phase flow systems. This relation considers the distribution of void fraction over the mixture volumetric flux profile using a distribution parameter term. This term is important because the dispersed phase flows with respect to the local flow rate. Therefore, the area-average velocity of the dispersed phase should reflect the effect of a gas phase distribution with respect to the flow profile. The relative velocity between the dispersed phase and the local volumetric flux is accounted for using a drift velocity term. The kinematic constitutive relation is given by

$$\frac{\langle j_g\rangle}{\langle\alpha\rangle} = \langle\langle v_g\rangle\rangle = C_0\langle j\rangle + \langle\langle V_{gj}\rangle\rangle \tag{1}$$

where j_g, α, v_g, C_0, j, and V_{gj} are superficial gas velocity, void fraction, gas velocity, distribution parameter, mixture volumetric flux, and drift velocity, respectively. The $\langle\rangle$ and $\langle\langle\rangle\rangle$ notations designate area-averaged and void-weighted mean values, respectively. The definitions for distribution parameter and drift velocity are given by (Zuber and Findlay, 1965)

$$C_0 = \frac{\langle\alpha j\rangle}{\langle\alpha\rangle\langle j\rangle} \tag{2}$$

$$\langle\langle V_{gj}\rangle\rangle = \frac{\langle\alpha V_{gj}\rangle}{\langle\alpha\rangle} \tag{3}$$

A common approach for evaluating the drift-flux parameters is with respect to data plotted on a $\langle j\rangle - \langle\langle v_g\rangle\rangle$ plane. Here, the distribution parameter is represented by the slope of the data trend while the drift velocity is given by the intercept of the data trend