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Drift-flux model for upward two-phase cross-flow in horizontal tube bundles

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ABSTRACT

In relation to void fraction prediction of cross-flow in horizontal tube bundle of shell-tube heat exchangers, a drift-flux correlation has been developed to meet the demand on the study of two-phase flow gas and liquid velocities, two-phase pressure drop, heat transfer, flow patterns and flow induced vibrations in the shell side. Two critical parameters such as distribution parameter and drift velocity have been modeled. The distribution parameter is obtained by constant asymptotic values and taking into account the differences in channel geometry. The drift velocity is modelled depending on the density ratio and the non-dimensional viscosity number. The relationship between the channel averaged and gap mass velocity has been discussed in order to obtain the superficial gas and liquid velocities in the drift-flux correlation. The newly developed drift-flux correlation agrees well with cross-flow experimental databases of air-water, R-11 and R-113 in parallel triangular, normal square and normal triangular arrays with the mean absolute error of 1.06% and the standard deviation of 4.47%. In comparison with other existing correlations, the newly developed drift-flux correlation is superior to other studies due to the improved accuracy. In order to extend the applicability of the newly developed drift-flux correlation to void fraction of unity, an interpolation scheme has been developed. The newly developed drift-flux correlation is able to calculate the void fraction of cross-flow over a full range with different sub-channel configurations in shell-tube type heat exchangers.

1. Introduction

Shell-and-tube heat exchangers are employed in engineering systems such as power generation and refrigeration, petroleum, chemical, nuclear and other related industries. The most common equipment includes kettle and thermosiphon type reboilers, evaporators, condensers and steam generators. These equipment generally consist of hundreds of several-meters-long tubes (Ribatski and Thome, 2007). Moreover, traditional heat exchanger design criteria as much as within ± 30% accuracy of the thermal-performance predictions by available heat transfer correlations (Dowlati and Kawaji 1999) lead to excessive production investments (Bell, 1981; Grant et al., 1983; Shah and Sekulic, 2003), wasted operational room (Niels, 1979; Schuller, 1982; Smith, 1985) and contaminated refrigerant leakage (Ribastski 2008). Thus, it is essential to minimize their dimensions by facilitating heat exchangers' heat transfer efficiency contributing to optimal installation, operation and maintenance expenses (Kanizawa et al., 2012). A comprehensive understanding of flow characteristics in the shell-side channel helps achieve this goal.

Over 50% of the process heat exchangers (Noghrehkar et al. 1996; Xu et al., 1998) generates two-phase flow in the shell side. Due to the complexity of the interactions between phases as well as the heat transfer of the shell-side cross-flow through the tube bundle, there have been limited studies on them. For example, in the shell side of a heat exchanger, upward cross-flow initiates as subcooled fluid and then flows along the heated horizontal tube bundles which contain the heated refrigerants inside. Phase change occurs as the cold fluid in the shell absorbs the heat from the refrigerants in the tubes.

A complete understanding of the flow structure requires the study of the two-phase pressure drop, flow patterns, heat transfer and flow-induced vibration. Liquid and vapor velocities are dependent on the void fraction (Godbole et al., 2011). Two-phase pressure drop estimation relies on the local density distribution of the shell-side two-phase flow (Consolini et al., 2006) which is based on the void fraction. Cheng et al. (2008) and Quibén and Thome (2007) also pointed out the dependency of the heat transfer coefficient on flow patterns requires the knowledge of void fraction. Void fraction and flow pattern transitions are intrinsically related

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which influences heat transfer in the heat exchanger. Excessive vibration in high flow rate systems due to fluid elastic instabilities such as steam generators leads to tube failure, fretting wear and corrosion, which should be avoided at design stage (Pettigrew and Taylor 2003). As pointed out by Khushnood et al. (2004), vibration excitation and damping mechanisms are also determined by void fraction and flow regimes.

Consequently, void fraction is an essential parameter to characterize the flow behaviors. However, void fraction measurement in cross flows over tube arrays is much more difficult than that in internal flows despite of several existing tube bundle cross-flow experiments. Therefore, only counted experiments on void fraction measurement were performed and the detailed hydrodynamics research of the cross-flow though tube bundle is still in infancy (Jensen 1989; Xu et al., 1998). For both very low void fraction (Iwaki et al., 2005) and very high flow void fraction (Kondo et al., 2014) conditions, even less accurate data is available due to technical inaccuracy. Furthermore, contemporary void fraction correlations including some relatively complicated empirical equations show restrictions in their prediction applicability.

In what follows, this paper aims to develop a drift-flux correlation for void fraction prediction in horizontal tube bundles of the shell-tube heat exchanger systems. Basic drift-flux model concept is introduced to highlight its applicability and importance in void fraction calculations for two-phase system. Literature survey on existing void correlations and databases is presented afterwards. The methodology of the newly developed drift-flux correlation follows and then its computational results of the void fraction are compared with other correlations and data.

2. One-Dimensional drift-flux model and existing correlations

This section briefly reviews the formulations and constitutive equations of the drift-flux model and discusses its application in various conditions. The drift-flux model (Zuber and Findlay, 1965) is a simplified form of the more detailed two-fluid model which is used in many current thermal-hydraulics system analysis codes (Ransom et al., 1982; Bajorek, 2008; Ishii and Hibiki 2010) and severe accident analysis codes (Allison et al., 1993; Gauntt et al., 2000; Van Dorsselaere et al., 2009; Wang et al., 2014). However, due to its simplicity and unique parameters representing the interfacial characteristics between phases to a wide range of two-phase systems with reasonable accuracy, the drift-flux model still plays a critical role in two-phase flow analyses.

2.1. One dimensional drift-flux model

The general expression of the one-dimensional drift-flux model is expressed 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, and j are the superficial gas velocity, void fraction, gas velocity and mixture volumetric flux, respectively. The relationships among these parameters are given by

$$j_g = \alpha v_g, \tag{2}$$

$$j_f = (1-\alpha)v_f, \tag{3}$$

$$j = j_g + j_f = Gx/\rho_g + G(1-x)/\rho_f, \tag{4}$$

where G and x are the mass velocity and quality. $\langle\rangle$ and $\langle\langle\rangle\rangle$ mean the area-averaged quantity over the cross-sectional flow area and void fraction weighted area-averaged quantity, respectively. C_0 and v_{gj} are, respectively, the distribution parameter and drift velocity as defined by Eqs. (5) and (6).

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

$$v_{gj} = v_g - j = (1-\alpha)\left(v_g - v_f\right) = (1-\alpha)v_r, \tag{6}$$

where $v_f$and v_r are the liquid velocity and relative velocity, respectively. The void fraction weighted drift velocity is given by

$$\langle\langle v_{gj}\rangle\rangle \equiv \frac{\langle\alpha v_{gj}\rangle}{\langle\alpha\rangle}. \tag{7}$$

The appropriate mean transport drift velocity is defined by

$$\overline{V_{gj}} \equiv \langle\langle v_g\rangle\rangle - \langle j\rangle = (C_0-1)\langle j\rangle + \langle\langle v_{gj}\rangle\rangle. \tag{8}$$

2.1.1. Distribution parameter

The distribution parameter C_0 depends on pressure, channel geometry and flow rate which are simplified as factors of density ratio ρ_g/ρ_f and Reynolds Number GD/μ_f (Ishii 1977). The distribution parameter approaches unity, when density ratio approaches unity. Thus distribution parameter can be represented by

$$C_0 = C_\infty - (C_\infty - 1)\sqrt{\frac{\rho_g}{\rho_f}}, \tag{9}$$

where C_∞ is the asymptotic value of the distribution parameter at $\rho_g/\rho_f = 0$. ρ_g and ρ_f are the gas and liquid phase densities. The density ratio scales the inertia effects of each phase in a transverses void fraction distribution (Ishii and Hibiki 2010). For a circular pipe, Ishii (1977) recommended C_∞ to be 1.2 and 1.35 for dispersed two-phase flows in circular and rectangular channels, respectively.

$$C_0 = 1.2 - 0.2\sqrt{\frac{\rho_g}{\rho_f}}, \tag{10}$$

$$C_0 = 1.35 - 0.35\sqrt{\frac{\rho_g}{\rho_f}}. \tag{11}$$

For other geometries such as sub-channel of rod bundles, Julia et al. (2009) gave C_∞ value ranging from 1.03 to 1.05 depending on the ratio of rod diameter over pitch distance, while Ozar et al. (2008) gave $C_\infty = 1.1$ for annular channel. In the bubbly flow regime for adiabatic flow, the non-drag force such as lift force (Hibiki and Ishii, 2007) governs the bubble distribution which affects the distribution parameter. Since the bubble size is an important parameter in determining the lift force, Hibiki and Ishii (2002b) correlated the distribution parameter with the bubble diameter as

$$C_0 = \left[C_\infty - (C_\infty - 1)\sqrt{\frac{\rho_g}{\rho_f}}\right]\left[1 - \exp\left(-22\langle D_{Sm}\rangle/D_H\right)\right], \tag{12}$$

where D_{Sm} is the Sauter mean diameter $D_{sm} = 6\langle\alpha\rangle/\langle a_i\rangle$ (Hibiki and Ishii 2002a), and D_H is the hydraulic diameter. a_i is the interfacial area concentration given by

$$a_i = \frac{3.02g^{0.174}}{D_H^{0.335}v_f^{0.239}}\left(\frac{\sigma}{\Delta\rho}\right)^{-0.174}\alpha\varepsilon^{0.0796}, \tag{13}$$

For boiling flow, Ishii (1977) extended Eq. (9) by adding a weighting factor to take into account the effect of wall bubble nucleation. The subcooled liquid in the core of the channel and wall nucleation delay the bubble travelling towards the core, providing $C_0 = 0$ at the onset of boiling. As the void fraction increases, the void distribution transits from the wall peak to the central peak