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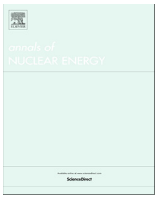

Flow pattern effect on two-phase pressure drops in vertical upward flow across a horizontal tube bundle

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ABSTRACT

Shell-side two-phase pressure drops under cross-flow condition play an important role in the operation of heat exchangers. However, no well-verified general correlation for predicting two-phase friction multipliers in horizontal tube bundles is available in the open literatures. In the present paper, based on a combination of Kanizawa and Ribastki flow regime criteria with the modified Mao and Hibiki flow regime criteria, the flow patterns of two-phase vertically upward flow across horizontal tube bundles in the open literatures were identified. The results show that flow patterns have a significant effect on two-phase friction multipliers. For the bubbly flow, finely dispersed bubbly flow, and annular flow, the mass velocity effect on two-phase friction multipliers can be neglected. However, the two-phase friction multipliers of cap bubbly flow and churn flow decrease with an increasing mass velocity. Then, a general dimensionless correlation in terms of the Martinelli parameter and the two-phase Froude number were developed, which is able to accurately predicting gas–liquid two-phase flow resistances of churn flow in staggered horizontal tube bundle under cross-flow condition. New correlations for predicting two-phase friction multipliers of bubbly flow, finely dispersed bubbly flow and annular flow both in staggered and in-line horizontal tube bundles were also developed and can give excellent representations for the existing data in the open literatures.

1. Introduction

Shell-side pressure drops play an important role in the design and operation of heat exchangers such as steam generators, condensers and evaporators. For example, as the primary side pressure boundary in nuclear power plants, the integrity of tubes in steam generators must be maintained, since the vibration and failure of tubes may lead to a release of contaminative primary coolant to the conventional island. The two-phase pressure drop in a horizontal tube bundle consists of three components: gravitation, friction and acceleration. Void fraction, which can be calculated by Feenstra et al. (2000) model, is the unique critical parameter to obtain gravitation and acceleration when the two-phase density can be regarded as a constant value. However, the two-phase frictional pressure drop is dependent on more critical parameters, such as physical properties, channel geometries, flow conditions, and so on. Correspondingly, numerous experiments have been carried out to investigate the effects of these key parameters on two-phase frictional pressure drop in vertically upward flow across a horizontal tube bundle.

A correlation suggested by Ishihara et al. (1980) can be used to calculate two-phase friction multipliers in horizontal tube bundles based on the following model (Lockhart and Martinelli, 1949):

$$\Phi_l^2 = \frac{\Delta P_{tp}^f}{\Delta P_l^f} = 1 + \frac{C}{X} + \frac{1}{X^2} \tag{1}$$

where C is a parameter with respect to flow conditions and channel geometries. ΔP_{tp}^f and ΔP_l^f are two-phase frictional pressure drop and single-phase frictional pressure drop in horizontal tube bundles, respectively. X is the Martinelli parameter, which can be defined as Tian et al. (2016):

$$X = \left(\frac{1-x}{x}\right)^{0.9} \left(\frac{\rho_g}{\rho_l}\right)^{0.5} \left(\frac{\mu_l}{\mu_g}\right)^{0.1} \tag{2}$$

Here, x is the mass quality. ρ_g and ρ_l are separately gas phase density and liquid phase density. μ_g and μ_l are dynamic viscosities of gas phase and liquid phase, respectively.

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Nomenclature

C	Flow resistance coefficient or parameter of two-phase friction multiplier (–)
d	Outer diameter of rods (m)
f	Frictional factor (–)
Fr	Froude number (–)
G	Mass velocity (kg·m^{-2}s^{-1})
J	Superficial velocity (m·s^{-1})
P	Pressure (Pa)
Re	Reynolds number (–)
S	Rod pitch (m)
x	Quality (–)
z	z-axis

Greek symbols

α	Void fraction (–)
Δ	Difference (–)
ε	Energy dissipation per unit mass (J·kg^{-1})
ρ	Density (kg·m^{-3})
μ	Dynamic viscosity (Pa·s)
X	Martinelli parameter (–)
Φ	Multiplier (–)

Subscripts

ann	Annular flow
Bub	Bubbly flow or finely dispersed bubbly flow
chu	Churn flow
exp	Experimental data
f	Friction
g	Gas phase
l	Liquid phase
m	Two-phase mixture
n	Index
pre	Predictions
t	Transverse
tp	Two-phase
$*$	Dimensionless

Acronyms

AF	Annular flow
BF	Bubbly flow
CF	Churn flow
FDBF	Finely dispersed bubbly flow

Ishihara et al. (1980) reported that their two-phase friction multiplier data can be predicted well by using Eq. (1) with a value of 8 for the C factor when $X < 0.2$. However, the deviations between the predictions and the data would be extremely large when $X > 0.2$ and $C = 8$. According to their analysis, this may be due to the effect of two-phase flow patterns, which should also be taken into consideration. However, none of correlations to predict C factor data for $X > 0.2$ was developed by Ishihara et al. (1980). Schrage et al. (1988) investigated the effect of flow pattern on two-phase friction multipliers in an in-line horizontal tube bundle with a value of 1.3 for the pitch-to-diameter ratio S_T/d. Their experimental results showed that the use of $C = 8$ did not give good representations of the two-phase pressure drop data. In addition, an obvious mass velocity effect on the two-phase friction multiplier was observed for $0.01 < X < 100$ and $54 \leq G \leq 683$ kg·m^{-2}s^{-1}. Then, Dowlati et al. (1990) conducted an similar experiment and concluded that the void fraction correlation developed by Schrage et al. (1988) underpredicted the actual values. The two-phase multiplier data obtained by Dowlati et al. (1990) exhibited strong effects of pitch-to-diameter ratio and mass velocity. For example, the two-phase friction multiplier data for $G > 260$ kg·m^{-2}s^{-1} and $S_T/d = 1.3$ could be predicted well with the use of $C = 8$. However, a strong mass velocity effect on two-phase friction multipliers was found for smaller mass velocity conditions. Besides, the best values of the C factor in in-line horizontal tube bundles increase with a pitch-to-diameter ratio, i.e. $C = 50$ for $S_T/d = 1.75$ while $C = 8$ for $S_T/d = 1.3$. Then, the effects of pitch-to-diameter ratio and mass velocity on two-phase friction multipliers in staggered horizontal tube bundles were investigated by Chan and Kawaji (1992). The experimental results indicated that the use of $C = 20$ could give fairly predictions for two-phase friction multiplier data when $G \geq 200$ kg·m^{-2}s^{-1}. However, the two-phase friction multiplier decreases with an increasing mass velocity for both the staggered tube bundles with $S_T/d = 1.3$ and $S_T/d = 1.75$ when $G < 200$ kg·m^{-2}s^{-1}. This same trend was also obtained in another experiment carried out by Tian et al. (2016). However, the best value of the C factor is 25 for $G \geq 200$ kg·m^{-2}s^{-1} when the tube arrangement is staggered and $S_T/d = 1.42$. Xu et al. (1998) investigated flow patterns and air-water two-phase pressure drop characteristics in an in-line horizontal tube bundle. The two-phase friction multiplier data could be correlated well by using the Martinelli parameter and a new defined dimensionless superficial velocity of gas phase. However, the predictions calculated by the correlation developed by Xu et al. (1998) did not agreed very well with the two-phase friction multiplier data, i.e. the developed correlation is able to predict 71.2 percent of the experimental data with a maximum deviation of ±20%.

It is worth noting that none of Dowlati et al. (1990), Chan and Kawaji (1992), Tian et al. (2016), Xu et al. (1998) conducted an thorough investigation on the relationship between flow patterns and two-phase friction multipliers, though Ishihara et al. (1980) suggested that the C factor may be dependent on flow patterns. Besides, the literature review indicates that new correlations are required to give better predictions for two-phase friction multipliers in both staggered and in-line horizontal tube bundles, especially for those under small mass velocity conditions. Therefore, in the present study, flow patterns of two-phase upward flow across horizontal tube bundles were first investigated. Then, the existing two-phase multiplier data obtained by previous investigators were reorganized and analyzed combined with flow patterns. New correlations in terms of flow patterns and the Martinelli parameter were developed to predict two-phase friction multipliers in horizontal tube bundles. These correlations were then tested by estimating the existing experimental data.

2. Two-phase flow patterns

Since flow patterns in two-phase vertical upward flow across a horizontal tube bundle are dependent on physical properties, channel geometries and channel size, continuous efforts (Agostini, 2008; Aprin et al., 2007; Grant and Chisholm, 1979; Kanizawa and Ribatski, 2016; Noghrehkar, 1997; Ulbrich and Mewes, 1994; Wen-peng and Fei-yu, 2012; Xu et al., 1998) have been performed on the flow regime identification. Based on the results reported by Mao and Hibiki (2017), five flow patterns can be generally observed in the open literatures, i.e. bubbly flow, cap bubbly flow, churn flow, finely dispersed bubbly flow, and annular flow.

Now that the general flow regime identification in horizontal tube bundles have been performed, the flow regime criteria is