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Void fraction and pressure drop during external upward two-phase cross flow in tube bundles – part II: Predictive methods

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ABSTRACT

The present paper is the Part II of a broad study concerning void fraction and pressure drop for air-water upward external flow across tube bundles. In the Part I, the experimental facility and the data regression procedures were described and the experimental results are presented and discussed. Initially, Part II presents a literature review concerning void fraction and pressure drop predictive methods available in the open literature for two-phase upward flow across tube bundles. Next, the methods from literature are compared among them and with the database presented in paper Part I. Significant discrepancies are observed among the predictive methods, and deviations as high as two orders of magnitude are verified among the predicted values of pressure drop. Then, a new void fraction predictive method is proposed based on the experimental results and on the minimum kinetic energy principle. This method provides satisfactory predictions of the results described in paper Part I and also of independent data from the literature. A new predictive method for frictional pressure drop during two-phase flow based on two-phase multiplier is also proposed. This method predicted 94% of the experimental data obtained in the present study within an error margin of ±30%, and also provides accurate predictions of independent results for triangular tube bundles gathered in the open literature.

1. Introduction

The first part of this study, Kanizawa and Ribatski (2016c), presents the experimental results obtained for triangular tube bundle with tubes of O.D. of 19 mm and transversal pitch per diameter ratio of 1.26. The experiments were performed for air and water mixtures close to atmospheric pressure and ambient temperature, comprising conditions of mass velocity up to 1515 kg/m²s and gas mass fractions up to 0.36. In the Part II, a state-of-the-art review concerning predictive methods for void fraction and pressure drop is presented. Comparisons are performed among the methods and the void fraction and pressure drop databases presented in Part I. In general, the methods for prediction of the frictional pressure drop show reasonable disagreement among them and also from the experimental results. In this context, it is important to highlight that frictional pressure drop results are estimated from measurements of the total pressure drop that includes also the acceleration and the gravitational parcels. For vertical two-phase flows across tube bundles, the gravitational pressure drop is a significant portion of the total pressure drop and its value is not measured but, generally, is calculated based on the void fraction estimative. So, the total pressure drop should be estimated based on the combination of the method for prediction of the frictional pressure drop and the corresponding method for void fraction used in the data regression analyses. Therefore, in order of attending this basic requirement and provide accurate predictions of the total pressure drop, new predictive methods for frictional pressure drop and void fraction are proposed based on the database described in paper Part I. By implementing these two methods together, satisfactory predictions are obtained of the experimental database gathered in the present study and independent data from literature.

2. Predictive methods from literature for pressure drop and void fraction

This item presents a literature review on predictive methods for void fraction and pressure drop. As pointed out in the Part I of this study, the number of studies concerning external

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Nomenclature

c_0	distribution parameter, non-dimensional
d	tube external diameter, m
g	gravitational acceleration, m/s²
G	mass flux, kg/m²s
j	superficial velocity, m/s
K	momentum coefficient, non-dimensional
L	tube length, m
S	slip velocity ratio, non-dimensional
s_1	transversal pitch, m
s_2	longitudinal pitch, m
u_g	*in situ* gas velocity (j_g/α), m/s
u_l	*in situ* liquid velocity ($j_l/(1-\alpha)$), m/s
u_{gj}	drift parameter, m/s
x	gas mass fraction, non-dimensional

Greek letters

α	void fraction, non-dimensional
μ	dynamic viscosity, kg/m.s
ρ	density, kg/m²
Φ^2	two-phase multiplier, non-dimensional
σ	surface tension, N/m
τ	transversal pitch per diameter ratio, non-dimensional

Subscripts

g	gas phase
l	liquid phase
l_0	mixture flowing as liquid
g_0	mixture flowing as gas
fs	free stream condition
sp	single-phase flow
HM	homogeneous model

Non-dimensional parameters

Capillary number	$Cap = \mu_l u_g/\sigma$
Froude number	$Fr_{l0} = G^2/(\rho_l^2 dg)$
Non-dimensional gas velocity	$j_g^* = j_g/\sqrt{gd[(\rho_l/\rho_g) - 1]}$
Lockhart and Martinelli parameter	$X_{tt} = ((1-x)/x)^{0.9} (\rho_g/\rho_l)^{0.5}(\mu_l/\mu_g)^{0.1}$
Reynolds number of liquid phase	$\mathrm{Re}_l = \rho_l j_l d/\mu_l$
Richardson number	$Ri = (\rho_l - \rho_g)^2 g\tau/G^2$
Weber number	$We = G^2 d/((\rho_l - \rho_g)\sigma)$

two-phase flows is considerably small compared with studies for internal flows, and, as consequence, the number of predictive methods for these flow parameters is also reduced.

2.1. Void fraction

Table 1 summarizes the databases used in the development of void fraction α predictive methods available in the open literature according to the authors' knowledge. According to this table, only Dowlati et al. (1990, 1992b) and Feenstra et al., (2000) performed measurements of the chordal void fraction, through the gamma attenuation technique γ, while the remaining studies performed measurements of the volumetric void fraction, based on the quick closing valve technique QCV.

As general behaviors, the void fraction increases with increasing gas mass fraction (or vapor quality) x, and mass velocity G (or mass flux). These behaviors are captured by the predictive methods listed in Table 1, except by the homogenous model, according to which the void fraction is independent of the mass velocity. It must be highlighted that some predictive methods, such as Kondo and Nakajima (1980) and Dowlati et al., (1990), present void fraction values different from unity for gas single-phase flow, thus it can be speculated that the applicability of these methods are restricted to reduced gas fractions.

Table 2 summarizes the void fraction predictive methods available in the open literature. The homogeneous model can be directly derived from the continuity equations written for both phases, and assumes the velocity slip ratio S equal to the unity. Kondo and Nakajima (1980) performed an experimental study for two-phase flow in kettle reboilers, therefore operating at very low velocity as shown in Table 1. So, in their predictive method the void fraction is basically a function of the gas superficial free stream velocity $j_{g,fs}$ and bundle geometry.

Schrage et al., (1988) proposed a predictive method by defining a multiplier factor to the void fraction estimated according to the homogenous model α_{HM}. In their model, the α_{HM} should be multiplied by 0.1 if the multiplier value is lower than 0.1. The multiplier factor is given as function of the Froude number of the mixture flowing as liquid Fr_{l0} and the vapor quality x.

Dowlati et al., (1990) proposed an empirical method based on non-dimensional gas velocity j_{g*}, as defined by Wallis (1969). Subsequently, Dowlati et al., (1992b), based on their database, adjusted the two-phase distribution c_0 and drift-flux u_{gj} parameters of the drift flux model proposed by Zuber and Findlay (1965). As given in Table 2, they proposed constant values for each parameter independent of the two-phase flow patterns. Based on their database, Delenne et al., (1997) *apud* Feenstra et al., (2000) adjusted a constant value for the two-phase distribution parameter of the drift flux model. In their method, the drift velocity u_{gj} is given by the relationship proposed by Zuber and Findlay (1965) for intube slug flow.

Xu et al., (1998), based on the approach presented by Butterworth (1975) and on their database, proposed a predictive method according to which the void fraction is given as a function of the Froude number of the two-phase mixture flowing as liquid Fr_{l0} and the Lockhart and Martinelli (1949) parameter X_{tt}.

Feenstra et al., (2000) proposed a correlation for the velocity slip ratio S based on their experimental results and experimental results presented by Dowlati et al., (1992b). In their method, the slip ratio is given as function of the Richardson Ri and Capillary Cap numbers. Due to the fact that Cap is a function of the in situ gas velocity u_g, which in turn, is a function of the void fraction, this method requires an iterative procedure for the estimative of the void fraction.

Table 1
Experimental conditions of databases used in the development of the void fraction predictive methods.

Author	Mixture	Config.	d [mm]	τ [-]	G [kg/m²s] up to	x [-] up to	Method
Homogeneous model	–	–	–	–	–	–	–
Kondo and Nakajima (1980)	Air-water	Triangular	25	1.08, 1.28, 1.40	3.2	0.16	QCV
Schrage et al. (1988)	Air-water	Square	7.94	1.08 ∼ 1.40	680	0.64	QCV
Dowlati et al. (1990,1992b)	Air-water	Triangular and square	12.7, 19	1.3, 1.75	818	0.33	γ
Xu et al. (1998)	Air-water	Square	9.79	1.25	658	0.68	QCV
Feenstra et al. (2000)	Air-water, R11, R113	Triangular	6.17 ∼ 19	1.3 ∼ 1.75	818	0.33	γ