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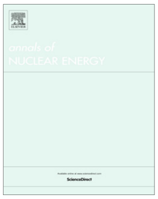

Hydrodynamics of two-phase flow in a rod bundle under cross-flow condition

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ABSTRACT

Pressure drop experiments were conducted for a vertical two-phase air–water flow across a horizontal staggered rod bundle under conditions of air quality ranging from 0.001 to 0.3 and mass velocity ranging from 80 to 500 kg/(m^2 s). The experimental data were thoroughly analyzed and compared with predictions from existing correlations. New developed expressions provided the most accurate predictions. The two-phase friction multipliers for $G \leqslant 200$ kg/(m^2 s), which show a strong mass velocity effect, could be fit well in terms of the Martinelli parameter and the dimensionless mass velocity. The new correlation developed for the two-phase friction multiplier was successfully tested in predicting the experimental data for $G \leqslant 200$ kg/(m^2 s) in previous experiments of other researchers. Distributions of velocity and turbulent intensity were also obtained from the numerical simulation on single-phase flow of water using the CFD code ANSYS FLUENT 14.0. The SST k–ω model was verified to be the best turbulent model to gain flow characteristics in the horizontal rod bundle under experimental conditions.

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. In particular, as the primary side pressure boundary in nuclear power plants, the integrity of tubes in steam generators must be maintained. In addition, the vibration and failure of tubes may result in a release of contaminative primary coolant to the conventional island. Since a comprehensive understanding of three-dimensional thermohydraulics distribution in steam generators can provide guidance for the design and protection of tubes, Steam-generator Thermohydraulics analysis code based on Fluent (STAF), which is a steady analysis code (Cong et al., 2013), is employed to obtain thermal–hydraulic parameters, including the localized velocity, temperature, density, pressure, quality, and void fraction. However, the resistance models used in STAF to calculate cross flow resistances in horizontal tube bundles lack experimental verification. Thus, experiments on pressure drops of cross flow in horizontal tube bundles are necessary.

The two-phase pressure drop in vertical cross-flow over horizontal tube bundles consists of three components: gravitation, friction and acceleration. To obtain the gravitation and acceleration, the void fraction is needed. For the calculation of the frictional pressure drop, the two-phase friction multiplier is employed based on the separated flow model.

1.1. Void fraction

Numerous calculations of the void fraction in horizontal tube bundles have been obtained. The void fraction (α) defined by several parameters, including the velocity ratio (S), the density of the liquid phase (ρ_L), the density of the gas phase (ρ_G) and the quality (x), which can be given by

$$\alpha = \left[1 + S\frac{\rho_G}{\rho_L}\left(\frac{1-x}{x}\right)\right]^{-1} \tag{1}$$

The value of the velocity ratio is considered a unit in the homogeneous model, based on the hypothesis that both the liquid phase and gas phase have the same velocity. However, the experimental data obtained by several authors (Schrage et al., 1988; Dowlati et al., 1990, 1992; Feenstra et al., 2000; Aprin et al., 2002) indicated that the homogeneous model dramatically overestimated values of the void fraction. In actual two-phase flow, the interface slip ratio is not a unit and should be considered. Kondo and Nakajima (1980) conducted the first experiment to measure the void fraction of two-phase air–water flow across tube banks. They found that the void fraction was pertinent to the superficial gas velocity instead of the liquid velocity. However, the results are not generally usable for rather low mass velocities ($G < 5$ kg/(m^2 s)). Schrage et al.

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Nomenclature

a	independent variable (–)
C	parameter of two-phase friction multiplier (–)
Cap	capillarity number (–)
d	outer diameter of rods (m)
f	frictional factor (–)
G	mass velocity (kg/(m^2 s))
k	turbulence kinetic energy (m^2 s^{-2})
N	number of rod rows (–)
P	pressure (Pa)
Re	Reynolds number (–)
Ri	Richardson number (–)
s	rod pitch (m)
S	velocity ratio (–)
u	standard uncertainty (–)
ω	specific dissipation rate (s^{-1})
x	quality (–)
y-plus	non-dimensional distance from the wall (–)
Greek symbols	
α	void fraction, (–)
δ	instrumental errors (–)
ε	turbulent dissipation rate (m^2 s^{-3})
ρ	density (kg/m^3)
Δ	difference (–)
X	Martinelli parameter (–)
Φ	multiplier (–)
μ	dynamic viscosity (Pa s)
Subscripts	
1	C factor 1
2	C factor 2
3	C factor 3
acq	acquisition system
exp	experimental data
F	friction
G	gas phase
homo	predictions computed by the homogeneous model
ins	instrument
L	liquid phase
pre	predictions computed by the developed correlations
tt	turbulent flow for both the liquid phase and the gas phase
Acronyms	
CFD	computational fluid dynamics
RNG	re-normalization group
SST	shear stress transport

(1988) measured the void fraction of a two-phase air–water cross-flow over a horizontal in-line tube bundle with a pitch-to-diameter ratio (s/d) of 1.3. The void fraction was found to be strongly dependent on the mass velocity and could be fit well in terms of Froude number and quality. Dowlati et al. (1990, 1992) investigated the void fraction using a gamma densitometer in horizontal tube bundles of in-line and staggered arrays with s/d equaled 1.3 and 1.75. A higher void fraction was obtained as the s/d increased for staggered tube bundles. However, this behavior was not observed for in-line tube bundles. In addition, void fractions in staggered tube bundle would be significantly greater than those in in-line tube bundles for a given mass velocity and quality. This conclusion was also found in results of Reinke (1987). To estimate void fractions, a new model was proposed by Dowlati et al. (1990, 1992) in terms of the dimensionless superficial gas velocity, which could be used for both in-line and staggered tube bundles. Xu et al. (1998) carried out experiments for an adiabatic, vertical up-and-down, two-phase flow across a horizontal in-line tube bundle with s/d equaled 1.28. The void fraction also showed a strong mass velocity effect and could be fit well in terms of the Martinelli parameter and liquid-only Froude number. Feenstra et al. (2000) proposed a void fraction model for upward cross-flow over a horizontal tube bundle based on physical processes, which could be applicable to the adiabatic air–water, steam-water, refrigerant 11 and diabatic R-113 mixtures. Aprin et al. (2002) measured the void fraction of N-pentane and propane in a horizontal tube bundle using an optical probe. They noted that the void fraction was dependent upon the liquid–gas density ratio.

1.2. Two-phase friction multiplier

A Martinelli-type model (Lockhart and Martinelli, 1949) was generally used to represent the two-phase friction multiplier (Φ_L^2) in a horizontal tube bundle:

$$\Phi_L^2 = 1 + \frac{C}{X_{tt}} + \frac{1}{X_{tt}^2} \tag{2}$$

where

$$X_{tt} = \left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_G}{\rho_L}\right)^{0.5}\left(\frac{\mu_L}{\mu_G}\right)^{0.1} \tag{3}$$

The C factor in Eq. (2) was pertinent to the total mass velocity, flow pattern, arrangement of rod bundles et al. Ishihara et al. (1980) obtained a value of 8 for the C factor. In that study, the shear-controlled flow data could be predicted well only for $X_{tt} < 0.2$ and flow patterns should be taken into account for $X_{tt} > 0.2$. Schrage et al. (1988) investigated effects of flow patterns and mass velocities on two-phase friction multipliers and proposed new correlations to evaluate C factors. They founded that a C value of 8 over-predicted their friction pressure drops data. Unfortunately, the effect of arrangements of rod bundles was not studied in their researches. Dowlati et al. (1990, 1992) obtained the two-phase friction pressure drop data for staggered and in-line rod bundles with different pitch-to-diameter ratios. For in-line rod bundles, higher two-phase friction multipliers were obtained with larger s/d ratios. However, no s/d ratio effect was seen in staggered rod bundles. The two-phase friction multiplier could be fit well in terms of the Martinelli parameter for $G > 200$ kg/(m^2 s) when suitable values of the C factor were used. However, strong mass velocity effects were observed for low mass velocities ($G < 200$ kg/(m^2 s)) in all bundles and correlations were not developed to predict these experimental data. Xu et al. (1998) developed an expression in terms of the dimensionless superficial velocity of gas and quality, which could be satisfactorily used to correlate the two-phase friction multiplier data for $G > 200$ kg/(m^2 s). However, deviations out of ±20% accounted for more than 30% of the proportion for $G \leqslant 200$ kg/(m^2 s).

1.3. Numerical simulation

Numerical simulations by a commercial CFD code can help a lot in understanding flow characteristics of upward flow across horizontal rod bundles. Serizawa et al. (1997) carried out numerical