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Pressure drop characteristics of two-phase flow in a vertical rod bundle with support plates

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HIGHLIGHTS

- Two-phase friction multiplier data in a vertical rod bundle were obtained and analyzed.
- A new correlation was developed to obtain two-phase frictional pressure drops in a vertical rod bundle.
- Two-phase multiplier of local pressure drop of support plates were obtained and analyzed.
- A new correlation was developed to obtain two-phase local pressure drops of support plates.

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ABSTRACT

Experiments have been conducted for single-phase water and two-phase air–water flow in a vertical seven-rod bundle with support plates. Measurements were made for two-phase pressure drops under conditions of total mass velocity from 200 to 850 kg m^{-2} s^{-1}, quality from 9×10^{-4} to 0.27 and pressure from 110 to 230 kPa. Single-phase experimental results show that new developed correlations to obtain frictional factors in the vertical rod bundle and loss coefficients of support plates were in good agreement with experimental data. With respect to two-phase results, the homogeneous flow model dramatically overestimated two-phase friction multipliers in vertical rod bundles, while the new developed correlation presented good predictions. When calculating two-phase pressure drops in support plates, a new defined two-phase multiplier of local pressure drop in support plates was suggested. The two-phase multiplier data of support plates, in which an obvious mass velocity effect was observed, could be fit well in terms of Martinelli parameter and a dimensionless mass velocity. The new correlation developed for two-phase multipliers of support plates was successfully in predicting the experimental data.

1. Introduction

Two-phase flow on the shell side of tube bundles is popularly encountered in heat exchangers such as condensers, evaporators and reboilers. Specifically, pressure drop characteristics in the inverted U-tube bundle of a steam generator are of vital importance in its safety and reliable operations. Flow-induced vibration between the vertical part of inverted U-tube bundles and support plates can result in serious failures of tubes, which may lead to a release of contaminative primary coolant to the conventional island. As a result, to get a fully understanding of two-phase pressure drop characteristics of U-tube bundles in a steam generator, it is necessary to carry out experiments to develop correlations to accurately predict pressure drops of two-phase flow in vertical rod bundles.

A number of investigations have been conducted on single-phase pressure drops in vertical rod bundles. Rehme (1972) reviewed experimental and theoretical results on pressure drop coefficients of vertical rod bundles in hexagonal arrangements by more than 60 authors. In that work, an upper limit for single-phase pressure drop coefficients of turbulent flow was obtained. He proposed that pressure drop coefficients were considerably dependent on Reynolds number, the shape of channels, the pitch-to-diameter ratio, instead of the number of rods. Beattie and Lawther (1981) investigated flow characteristics of vertical upward flow of water through a vertical seven-rod bundle with spacers under atmospheric pressure. He concluded that flow characteristics when rod spacer grids are installed were quite different from those for bare rod bundles. Cheng and Todreas (1986) developed specific

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Nomenclature

C	parameter of multipliers (–)
f	single-phase frictional factor (–)
g	gravitational acceleration (m s^{-2})
G	mass velocity (kg m^{-2} s^{-1})
K	single-phase loss coefficient of support plates (–)
L	vertical height between pressure tap 2 and 3 (m)
P	pressure (Pa)
Re	Reynolds number (–)
U	superficial velocity (m s^{-1})
x	mass quality (–)
z	z-axis (–)

Greek symbols

α	void fraction (–)
ρ	density (kg m^{-3})
Δ	difference (–)
θ	inclination angle of tubes (°)
γ	surface tension (N m^{-1})
X	Martinelli parameter (–)
Φ	multiplier (–)
μ	dynamic viscosity (Pa s)
σ	standard deviation (–)
η	deviation (–)

Subscripts and superscripts

2–3	pressure tap 2–3
4–5	pressure tap 4–5
atm	atmospheric
ave	average
e	equivalent
f	frictional
g	gravitational
l	liquid-phase
l,exp	experimental liquid-only two-phase friction multipliers in rod bundles
$l0$,exp	experimental liquid-only two-phase friction multipliers in support plates
l,pre	predictions of liquid-only two-phase friction multipliers in rod bundle
$l0$,pre	predictions of two-phase multiplier in support plates
m	index
n	index
s	system
t	total
v	gas-phase
tp	two-phase
tt	turbulent
*	dimensionless

correlations for bundle frictions factors, which could be used to predict the experimental data within at least ±14% with a 92% confidence interval for turbulent flow and within ±30% for laminar flow. Yang and Chung (1996) measured pressure drops of water in a 5 × 5 rod bundle with spacer grids for Reynolds numbers from 10^4 to 10^5. The bundle friction factor was slightly higher, about 2.5%, than predictions calculated by Blasius correlation. In addition, a smaller pressure drop coefficient of spacers was obtained with an increasing Reynolds number. Sadatomi et al. (2004) conducted pressure drop experiments with water in a 2 × 3 vertical rod bundle at atmospheric pressure. Compared with predictions by Blasius correlation, the single-phase friction factor data were about 10% higher in the range of Reynolds numbers between 3×10^3 and 2×10^4.

Numerous investigators have used a friction multiplier to calculate two-phase frictional pressure drops in pipes. Lockhart and Martinelli (1949) carried out pressure drop experiments of adiabatic two-phase flows passing through 1.5–25.8 mm pipes. Martinelli parameter was proposed and used to compute two-phase bundle friction multipliers in horizontal pipes. Baroczy (1966) proposed an accurate correlation in which effects of fluid property and mass velocity were taken into account. Nevertheless, the correlation was not generally applicable due to its complication in the application. Mass velocity effect was also considered in Chisholm (1973) correlation, which was widely used to predict two-phase frictional pressure drop in tubes. Besides, Armand et al. (1959), Thom (1964) and Friedel (1979) also developed correlations to calculate two-phase friction multipliers in vertical or horizontal tubes. To the author's knowledge, there have been a few correlations for two-phase pressure drops in vertical rod bundles. Grillo and Mazzone (1972) carried out single- and two-phase pressure drop experiments in a 6 × 6 rod bundle at 70 atmospheric pressures. The bundle friction multipliers and the two-phase loss coefficients of spacers exhibited strong effects of steam quality and mass velocity. Most predictions were in good agreement with the experimental data when a suitable value of the slip ratio was used. Sadatomi et al. (2004) concluded that a simple, one-dimensional, one-pressure two-fluid model could be employed to predict two-phase pressure drops well by use of appropriate equations of wall friction and interfacial friction forces. Lu (2008) conducted extensive experiments for single- and two-phase flow through a 2 × 2 rod bundle with the pitch-to-diameter ratio of 1.625. The deviations between the experimental data and predictions by Chisholm (1973) correlation were quite large. Effects of channel geometry and surface tension on two-phase friction multipliers were observed.

The literature review indicates that single-phase pressure drops in rod bundles are dependent on several parameters, including arrangements of rod bundle, channel geometries and pitch-to-diameter ratios. In addition, most existing correlations were developed to obtain two-phase pressure drops in pipes. However, these correlations were not verified to be applied to rod bundles. Besides, two-phase pressure drop data of support plates in published literatures are quite few. In order to obtain accurate correlations to calculate pressure drops in rod bundles and across support plates, new correlations are needed to develop. Therefore, in the present study, pressure drops of single- and two-phase flow across a vertical rod bundle with support plates were measured. New correlations for single-phase loss coefficients and two-phase multipliers were developed.

2. Test facility description

The test loop is shown in Fig. 1. Compressed air with a maximum flow rate of 13 m^3 min^{-1} was measured by two vortex flowmeters at high gas flow rates, and with a procession vortex flowmeter at low flow rates. Water stored in the tank was delivered by the centrifugal pump with a capacity of 30.0 t h^{-1}. The air–water mixture traveled up through the test section with a vertical rod bundle inside. Then the mixture returned into the water tank. A copper-constantan thermocouple and three Rosemount pressure transducers were installed in the branch line contained vortex flowmeters. They were employed for measuring the temperature and pressure of air to obtain the density of air.

The test section, illustrated in Fig. 2, consisted of a circular channel with an inner diameter of 75.44 mm where seven heater rods located in an equilateral triangular array. The pitch-to-diameter ratio was 1.424. The upper and lower support plates with a