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Local void fraction and heat transfer characteristics around tubes in two-phase flows across horizontal in-line and staggered tube bundles

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ABSTRACT

This study investigated the local characteristics of void-fraction distribution and heat transfer around tubes in two-phase flows under adiabatic conditions using vertical duct test sections with inner dimensions of $90 \times 90\,mm^2$. Two kinds of test sections, in-line and staggered tube bundles, each containing five columns and eight rows, were employed for the measurements. The tube diameter of each was 15 mm, and the pitch-to-diameter ratio was 1.5 for both bundles. The working fluids were air and water, and the experiments were performed under atmospheric pressure in a temperature range of 20–25 °C. Superficial liquid velocity, J_L, and gas velocity, J_G, ranged from 0.1 to 0.3 m/s and 0.03 to 1.19 m/s, respectively. Two-dimensional void-fraction distributions were obtained using X-ray radiography and the local heat-transfer coefficients were measured using a platinum wire electrode placed on a tube that could be rotated. In the experiments, the time-averaged void fraction increased at the maximum and vertical minimum gaps for the in-line tube bundle, whereas the void fraction increased upstream of the tubes for the staggered tube bundle. In the bubbly flow condition, enhancement of the heat transfer by bubbles motion clearly occurred between ± 90 and 180° for the in-line tube bundle, and increased all over the pipe for the staggered tube bundle. The increase in the local heat transfer coefficients by bubbles motion was more apparent for the in-line tube bundle. The average heat transfer coefficient in the staggered tube bundle was higher than that in the in-line tube bundle in the bubbly flow regime, whereas the results were opposite in the intermittent flow regime.

1. Introduction

Knowledge of the two-phase flow characteristics across horizontal tube bundles in heat exchangers such as steam generators in pressurized water reactors, PWRs, and kettle reboilers is important. The void fraction and pressure drop in the flow channel are important parameters for predicting these flow characteristics, fluid oscillation, and heat transfer. Consequently, numerous experimental studies have been carried out in test loops with horizontal tube bundles to clarify two-phase flow phenomena.

Xu et al. (1998) compared the flow pattern, void fraction, and pressure drop in vertical upward and downward flows. Using an in-line tube arrangement and a pitch-to-diameter ratio, p/d, of 1.28, they showed the variation of void fraction with flow direction. Ulbrich and Mewes (1994) focused on flow regime clarification. They compared their experimental results with results associated with several tube geometries presented in the literature and proposed a new flow pattern map. Subsequently, they concluded that further investigations considering geometry factors such as pipe diameter and pitch were required.

Kondo and Nakajima (1980) investigated the spatial-average void fractions in staggered tube bundles with three different p/d conditions and proposed an empirical equation for predicting the mean void fraction containing the pitch effect. Dowlati et al. (1990, 1992) investigated the pressure drop and void fraction in in-line tube bundles with p/d 1.3 and 1.75 and showed that the two-phase pressure drop increased with p/d. They also investigated the pressure drop and the void fraction in staggered tube bundles, in which case they concluded that p/d had no effect on theses parameters. McNeil et al. (2012) investigated void fraction at minimum and maximum gaps between tubes in in-line bundle using the γ-ray, and compared the difference of the void fraction. They showed that the void fraction at the maximum gap is suitable to use for the drift flux model. For these experimental studies, the γ-ray density meter is a powerful tool for measuring void

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fraction although the spatial resolution for the measurement is limited.

Noghrehkarm et al. (1999) employed an electrical resistivity void probe to evaluate the local void fraction and further proposed a method to identify the flow regime based on the probability density function (PDF) of the signal. Aprin et al. (2007, 2011) used an optical fiber probe to obtain the local void fraction in a staggered tube bundle. However, many of these studies evaluated the local void fraction at several measurement positions in the tube bundles, and did not conduct sufficient two-dimensional void-fraction distributions in the bundles. To observe the local liquid velocity fields and bubbles motion around the tubes for in-line and staggered arrays, particle image velocimetry (PIV) was utilized by Iwaki et al. (2005). They reported that the wake regions of tubes made the void fraction distributions in staggered bundles uniform. Furthermore, they evaluated average void fractions using image processing and showed that the void fraction in staggered bundles is slightly higher than that in the in-line tube bundle in bubbly flow at a void fraction of less than 0.03.

Chan and Shoukri (1987) investigated the heat-transfer coefficient in in-line array tubes under pool boiling. Their results indicated that the heat-transfer coefficients in the upper row tubes were higher than those in the lower row tubes. Consequently, they concluded that the heat-transfer process was strongly influenced by the two-phase convection effects under low-quality conditions. Dowlati et al. (1996) investigated the average boiling heat transfer in in-line array tubes and showed that the heat-transfer coefficient increases with the heat flux in the nucleate boiling region. Burnside et al. (2001) investigated the heat-transfer coefficient along the flow direction and showed that the coefficient decreased marginally as the bundle row increases. Karas et al. (2014) investigated the heat-transfer coefficient around a tube with the aid of an electrochemical technique that enabled them to obtain the local heat transfer around the tube. However, the relation between the local void fraction and the heat transfer around the tube was not fully investigated.

It is known that bubbles motion agitates the liquid phase, resulting in increased heat transfer in the nucleate boiling region of two-phase flows. Hence, clarification of the relation between bubbles motion and heat transfer is important for optimizing the heat exchanger. This study was conducted with the objective of clarifying the local characteristics of void-fraction distribution and heat transfer around tubes in two-phase flows under adiabatic conditions. In particular, focus was placed on the flow regime of bubbly and intermittent flows that mainly appear in the upstream region of the heat exchangers. In this study, two-dimensional void-fraction distributions were measured using X-ray radiography, and the heat-transfer coefficients around each tube obtained using a platinum wire placed on a measurement tube. Subsequently, the results obtained for in-line and staggered tube bundles at a pitch-to-diameter ratio of 1.5 were compared.

2. Experimental setup

2.1. Experimental loop and test sections

A schematic diagram of the experimental facility is shown in Fig. 1. The test section was a vertical duct with a cross-section of 90 × 90 mm^2. Water was circulated through a liquid injector located at the bottom of this test section. Further, air was injected into the test section through two porous tubes made of polypropylene (Spacy Chemical Ltd., P-200) with a mean pore-diameter of 200 μm and porosity of 38%. The porous tubes were located at its base in a direction perpendicular to the tube bundles. The air flow rates were measured in each porous tube using mass flow meters (HORIBA Ltd., MF-F). We employed two maximum flow rate ranges: 50 L/min and 200 L/min. The accuracy of the flowmeters was ± 3% at full scale. The water flow rate was measured using a paddle wheel flowmeter (AICHI TOKEI, ND20) with an accuracy of ± 2% in the reading scale. The two-phase mixture flowed upward through tube bundles set in the test section. The

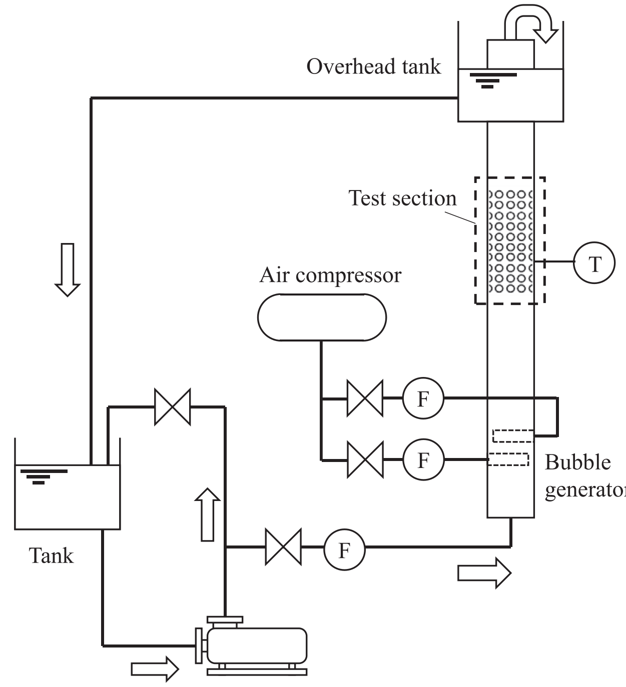

Fig. 1. Experimental test loop.

distance between the air injector and the bottom of the bundle was approximately 650 mm, and the top of the tube bundle was approximately 670 mm below the water surface in the overhead tank.

As shown in Fig. 2, two different tube bundles were employed for the measurements: (1) an in-line tube bundle with eight rows of three full tubes and two half tubes on the walls; (2) a staggered tube bundle with eight rows. The tubes were 90 mm long and the outer diameter, d, was 15 mm in both bundles. The tubes pitch, p, was 22.5 mm and the pitch-to-diameter ratio, p/d, was 1.5.

The experiments were performed at 20–25 °C with varying superficial liquid velocity, J_L, from 0.1 to 0.3 m/s, corresponding to mass flux, G, from 100 to 300 kg/(m^2s) and superficial gas velocity, J_G, from 0.03 to 1.19 m/s under atmospheric pressure. The superficial velocities and the mass flux were defined at the minimum cross-sectional area, labelled "A" in Fig. 2.

A high-speed camera (FASTCAM SA 1.1, Photron Ltd.) with a frame rate 1000 fps and shutter speed 1/2000 was employed to observe the flow regimes in two-phase flow.

2.2. X-ray radiography

X-ray radiography is based on the difference in X-ray attenuation resulting from a material and its thickness. The X-ray attenuation caused by water is higher than that caused by air because of the difference in their densities. Two-dimensional void-fraction distributions can be calculated from the brightness distributions based on the characteristics of the X-ray attenuation in the medium. Thus, it is known that the void-fraction distribution is obtained by processing three images—gas-filled, liquid-field and two-phase mixture-filled. Assuming that the intensity of the X-ray is proportional to the brightness distribution on the x-y plane, $S(x, y)$ can be expressed as follows:

$$S_G(x,y) = A(x,y)\exp[-\rho_M \mu_{mM} t_M(x,y)] + O_G(x,y) \quad (1)$$

$$S_L(x,y) = A(x,y)\exp[-\rho_M \mu_{mM} t_M(x,y) - \rho_L \mu_{mL} t(x,y)] + O_L(x,y) \quad (2)$$

$$S_{TP}(x,y) = A(x,y)\exp[-\rho_M \mu_{mM} t_M(x,y) - \{1-\alpha(x,y)\}\rho_l \mu_{mL} t(x,y)] + O_{TP}(x,y) \quad (3)$$

where A is the gain, O is the offset, ρ is the density, μ_m is the mass