International Journal of Heat and Fluid Flow 000 (2016) 1–10

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijhff

Void fraction and pressure drop during external upward two-phase crossflow in tube bundles – part I: Experimental investigation

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ARTICLE INFO

Article history:
Received 16 July 2015
Revised 26 January 2016
Accepted 4 April 2016
Available online xxx

Keywords:
Void fraction
Capacitive sensor
Pressure drop
Tube bundle

ABSTRACT

The present paper is the part I of a broad study concerning void fraction and pressure drop for air-water upward external flow across tube bundles. Experimental results were obtained for liquid and gas superficial velocities ranging from 0.02 to 1.50 m/s and 0.20 to 10.00 m/s, respectively. Void fraction measurements were performed for bubbly flow using a capacitive probe. The test section consisted of a triangular tube bundle counting with 19 mm OD tube and transverse pitch of 24 mm. Initially, the paper describes the test facility and the data regression and experimental procedures. Then, the pressure drop and void fraction measurements are validated based on tests for single-phase flow and quiescent liquid conditions, respectively. Finally, the experimental data are presented and analyzed. In the second part of this study (Part II), a literature review on predictive methods for void fraction and pressure drop is presented. Additionally, these methods are compared with the database presented in Part I and new predictive methods for void fraction and frictional pressure drop are proposed.

1. Introduction

According to Noghrehkar et al. (1999) and Green and Hetsroni (1995), more than half of shell-and-tube heat exchangers in industry operates under two-phase flow conditions in the shell-side; nonetheless, the number of researches and publications focused on external two-phase flows is considerably lower than those for in-tube flow. Consequently, the knowledge and understanding of the flow phenomena during external two-phase flows is still limited. In this context, Aprin et al. (2007) recommended further studies to improve the knowledge about two-phase external flow across tube bundles.

Motivation for investigation of void fraction

Void fraction is one of the most important two-phase flow parameters, being directly related to accelerational and gravitational pressure drop parcels. As pointed out by Kondo (1984) for reduced mass velocity, such as observed in kettle reboilers, the gravitational pressure drop parcel is dominant; therefore accurate estimative of void fraction is essential for an appropriate design of the pumping system.

The void fraction is defined as the temporal average of the proportion of gas phase in a given geometric domain. Thus, local, chordal, superficial (also named in the literature as area averaged void fraction) and volumetric void fractions can be defined. In this paper, when not specified, void fraction refers to the cross-sectional area averaged gas fraction.

Taitel and Dukler (1976) proposed a flow pattern map for horizontal and near to horizontal intube flow by adopting the liquid height, which is directly related to the void fraction, as the main parameter for the definition of transition criteria; therefore, the local flow pattern depends on the void fraction value. Based on the flow pattern map proposed by Wojtan et al. (2005a), Wojtan et al. (2005b) and Moreno-Quibén et al. (2009a,b) developed phenomenological predictive methods for heat transfer coefficient and pressure drop, respectively, during flow boiling in horizontal tubes. They defined distinct relationships for these parameters according to the flow pattern. Thus, it is logical to conclude that the heat transfer coefficient and frictional pressure drop parcel for intube flows depend on the void fraction. Such a conclusion can be extended to external flows.

Chan and Banerjee (1981) indicated void fraction as a key parameter for the evaluation of surface dryout, and, consequently, its prediction is fundamental for the safety analysis of heat ex-

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http://dx.doi.org/10.1016/j.ijheatfluidflow.2016.04.012
0142-727X/

Nomenclature

d	tube external diameter, m
g	gravitational acceleration, m/s^2
G	mass flux, kg/m^{2}s
H	height difference, m
j	superficial velocity, m/s
s_1	transversal pitch, m
x	gas mass fraction, non-dimensional

Greek letters

α	void fraction, non-dimensional
μ	dynamic viscosity, kg/m.s
ρ	density, kg/m^2
τ	transversal pitch per diameter ratio, non-dimensional

Subscripts

g	gas phase
l	liquid phase
$diff$	relative to the pressure taps

Non-dimensional parameter

Reynolds number of liquid phase $\mathrm{Re}_l = \rho_l j_l d/\mu_l$

changers. In nuclear reactors, the dryout would lead to the surface burnout, with consequent damage of its primary circuit.

The fluid inventory of a thermal system can be estimated based on the void fraction. In the refrigeration industry, the correct estimative of the fluid inventory is a key factor in the analysis of economic viability of a system, since the refrigerant represents a considerable parcel of the total cost. Moreover, Ribatski (2009) showed that the leakages in heat exchangers are inevitable, and that they are proportional to the total amount of refrigerant contained in these devices. Consequently, the minimization of the amount of fluid in a refrigeration system is essential to avoid overcharging of the system, and to reduce the amount of leakages.

Pettigrew and Taylor (2004) performed an experimental and theoretical study focused on the investigation of dynamic damping of the bundle subjected to flow induced vibrations (FIVs). According to these authors, the damping effect of the FIVs is composed of two parcels, one related to the viscous dissipation due to the tube motion across the fluid, and the other related to the detuning effect of tube and fluid interaction during two-phase flow, similar to observed by Carlucci and Brown (1983) for axial flows. Based on this hypothesis, Pettigrew and Taylor (2004) proposed a predictive method for the second parcel of damping effects given as a function of the void fraction. Therefore, void fraction is also essential for the evaluation of dynamic aspects of heat exchangers.

Experimental methods for void fraction evaluation

The quick closing valve technique has been extensively used for the evaluation of the volumetric void fraction for internal and external two-phase flows, e.g. Xu et al. (1998) and Schrage et al. (1988). This method provides volumetric void fraction measurements (also known as gas holdup) instead of area averaged void fraction. Nonetheless, it is important to highlight that under conditions of low pressure drop, channel with uniform cross section and developed flows, the values of volumetric and area averaged void fraction are similar.

Capacitive sensors are frequently employed to the evaluation of void fraction during two-phase flows. However, as mentioned by Falcone et al. (2009), this technique does not capture the effect of the flow pattern on the relationship between void fraction and capacitance, viz. distinct phases distribution corresponding to similar void fraction can provide different capacitance signals. Chun and Sung (1986) investigated two-phase flows inside horizontal tubes using strips and rings electrodes geometries. For a given void fraction and keeping the electrode geometry, they found that the relative capacitance for annular flow is higher than for stratified flow. This fact precludes the direct determination of void fraction through the flow capacitance without the previous knowledge of the local flow pattern. Based on capacitive sensors, Watanabe et al. (2012) evaluated the global void fraction in a model of PWR (Pressurized Water Reactor) steam generator. As far as the present authors know, capacitive sensoring systems were not employed to evaluate area averaged void fraction for two-phase flows across tube bundles.

Prasser et al. (1998) suggested wire-mesh sensors for the evaluation of area averaged void fraction for intube flows. This method is intrusive, presents low response time and its resolution depends on the mesh size. According to the knowledge of the present authors, until now, wire-mesh sensors were not applied to external flows.

Ursenbacher et al. (2004) developed an optical method for the measurement of void fraction for intube horizontal flow of refrigerants. The method is based on the addition of fluorescent dye to the refrigerant that is excited by a laser sheet perpendicular to the tube axis. Then, flow images are captured through a high-speed camera. Based on the fact that the fluorescent dye is contained only by the liquid phase, the void fraction is determined through analysis of the flow images. Refractions on the gas-liquid interface make this approach inappropriate for stratified flows. Also based on the addition of fluorescent dye to a liquid, Kanizawa (2014) developed a system to evaluate the superficial void fraction for external flows across tube bundles. In this study, Kanizawa (2014) obtained void fraction experimental results for bubbly flow under conditions of low gas velocities.

Iwaki et al. (2005) performed a study concerning the visualization of two-phase flow across regular-square and triangular tube bundles. These authors estimated the void fraction based on the size and concentration of bubbles inferred from analyses of flow images.

Gamma-ray densitometry is considered one of the best options for measurement of chordal void fraction (line averaged void fraction), despite its disadvantages concerning safety aspects, shielding requirements, high cost and slow response time. Due to this last aspect, this technique is recommended for the evaluation of time averaged void fraction, rather than transient measurements. For external flows across tube bundles, except by the regions close to the shell wall, the chordal void fraction between adjacent tubes is almost constant along to the tube length. Consequently, the chordal void fraction given by the gamma attenuation technique using a single beam between two adjacent tubes is similar to the surface averaged void fraction. Feenstra et al. (2000) and Dowlati et al. (1990, 1992) obtained void fraction measurements during two-phase flow across tube bundles using gamma-ray densitometry.

Noghrehkar et al. (1999) performed local void fraction measurements during external two-phase flows using a resistive probe. Even though this technique presents advantages as fast response and reduced cost, it does not provide information regarding the cross sectional and the volumetric proportion of phases. Noghrehkar et al. (1999) also evaluated the flow patterns based on the local void fraction signal using a procedure somewhat similar to the one used by Jones and Zuber (1975) in their classical paper.

Motivation for the investigation of pressure drop

Pressure drop is also a critical parameter for the design of thermal systems, because is directly related to the pumping power, and