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Comparison of local interfacial characteristics between vertical upward and downward two-phase flows using a four-sensor optical probe

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ABSTRACT

To model the interfacial transfer terms more accurately in two-fluid model as well as to further comprehend the intrinsic mechanism for downward two-phase flows, more information that involves local interfacial parameters is required. The local interfacial characteristics in upward and downward bubbly flows were investigated separately in a 50.8 mm inner-diameter round pipe. A four-sensor optical probe was used in the measurement of local interfacial parameters, including void fraction, interfacial area concentration (IAC), bubble frequency, interfacial velocity and Sauter mean diameter. The radial profiles of these parameters in downward flows were presented and compared with that in upward flows. In general, the void fraction shows a core-peaked distribution for the downward flow at low void fraction, but shows a wall-peaked distribution for the upward flow; while at high void fraction, it has an off-center-peaked distribution for the downward flow but a core-peaked distribution for the upward flow. Also, under relative high void fraction conditions, the profile of Sauter mean diameter presents a pronounced maximum in the channel center for the upward flow whereas near the channel wall for the downward flow. Additionally, with an increase in the gas flow rate, the flat profiles of interfacial velocity transform to power-law shapes in the upward flows but to that with the velocity increasing along the radius for the downward flows.

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1. Introduction

Downward two-phase flows are frequently encountered in various industrial equipments, such as nuclear reactors, energy transfer systems, chemical process systems and some other industrial systems. For instance, when the loss of coolant accident (LOCA) or loss of heat sink accident (LOHS) emerges in light water reactors, the steam generator may run in the mode of co-current downward two-phase flow. Consequently, to make a better countermeasure addressing the reactor accidents and to meet the requirement of safety analysis, it is of increasing significance to elucidate the characteristics of downward two-phase flow.

To have a profound knowledge of the two-phase flow, much effort has been devoted to investigating upward flows involving the flow patterns, void fraction, pressure drop as well as local interfacial characteristics. However, those for vertical downward two-phase flow, especially of the interfacial characteristics, are comparatively scarce.

Flow patterns (or flow regimes) and void fraction, one of the key parameters in two-phase flow, have been researched earliest and mostly. Golan and Stenning [1] proposed flow regime maps for a vertical downward flow and made a comparison with that in the vertical upward flow. Oshinowo and Charles [2,3] categorized the flow patterns into six regimes for the downward flow. Due to the subjectivity of researchers in the observation and identification of flow patterns as well as the individual experimental conditions, the flow regime maps may be discrepant with each other. The common flow patterns that are observed by most of the researchers [4–7] include bubbly, slug, churn-turbulent, and annular flows. With respect to the investigations of the flow patterns, some correlations that are based on the drift flux model for calculating the void fraction in downward flows were proposed [4,8–10], and meanwhile some others that are independent on the flow regimes were also put forward [11,12]. Swanand et al. [7] reported that the correlations developed for vertical upward flow are able to predict the void fraction in downward orientation, among which the correlation developed by Gomez et al. [13] was the best.

Furthermore, Wang et al. [14], Kashinsky et al. [15,16] and Sun et al. [17,18] have done some investigations on the local flow characteristics in vertical downward flow. In [14], the radial profiles of

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void fraction, liquid velocity and Reynolds stress were measured and a mechanistic model to predict the radial void fraction distribution was proposed, in which the turbulence structure and the lateral lift force were considered. In [15,16], the same parameters as presented in [14] were obtained, and a numerical simulation of the downward bubbly flow to predict momentum- and mass-transfer processes was performed. In [17,18], an improved laser Doppler anemometry (LDA) system was employed to measure the local axial liquid velocity and its fluctuation. In above-mentioned works [14–18], all of the investigators pointed out that the presence of bubbles tends to flatten the radial profile of liquid velocity, and the maximum liquid velocity may occur off the pipe center. However, among previous studies on the downward two-phase flow, only a few were about the local interfacial characteristics [5,19–21]. Hibiki et al. [20] proposed a classification of phase distribution patterns for downward flows, namely, (i) off-center peaked, (ii) bell-typed, and (iii) core-peaked distributions. The mechanisms for determining the latter two patterns can be well analyzed with the balance between the lift force and the wall force exerted on the bubbles [20]; unfortunately, a widely accepted viewpoint has not been obtained to explain the former one. In [19,21], the bubble coalescence and breakup, as dominant mechanisms in the interfacial area transport, were examined, which revealed that the transport is dependent on the void fraction, bubble size and liquid velocity. On the basis of the interfacial area transport equation for upward flows, Ishii et al. [5] developed a new one for downward flows and found its predictions agree well with the experimental data.

In contrast to vertical upward two-phase flow, some definite differences were observed in downward two-phase flow, which may arise from the buoyancy force that acts on the bubbles in an opposite direction to the flow. For instance, bubbles tend to migrate toward the pipe center in downward flow, but toward the wall region in upward flow [14]; the least void fraction required for cap bubble formation in downward flow is lower than that in upward flow [19]; the maximum liquid velocity may occur off the pipe center for downward flow but always at the pipe center for upward flow [14–16,18]; the liquid turbulence is smaller in downward flow compared with that in upward flow [18], and hence the impact of turbulent eddies on bubble breakup is weakened relatively in downward flow [5].

The similarities and differences in flow patterns, void fraction and pressure drop between vertical downward and upward two-phase flows have been reported in some literature. While a systematic comparison on local interfacial characteristics for both orientations is seldom seen by far. In view of the previous research on upward and downward flows, it should become relatively straightforward to comprehend the local interfacial characteristics as well as to evaluate and improve the theoretical models for the downward flow, if a comparison was made on the basis of the available knowledge of upward flow. For these reasons, experiments were preformed to obtain the local interfacial parameters by using a four-sensor optical probe for both the downward and upward flows. Parameters obtained include void fraction, interfacial area concentration (IAC), bubble frequency, interfacial velocity and Sauter mean diameter. Based on the experimental results, definite similarities and differences in local parameter distributions between downward and upward flows were presented.

2. Optical probe measurement approach

To obtain local IAC as well as the other interfacial parameters for perfecting the two-fluid model, researchers have attempted various measurement methods, among which the electrical and optical probes are the two most widely used techniques. In the past several decades, the multi-sensor probe was employed extensively to study the time-averaged void fraction and IAC in two-phase flow [22–26]. Using a double-sensor probe, Zhao et al. and Tian et al. [27,28] obtained some experimental results of these local parameters. However, when the interfacial lateral motion prevails, i.e. the flow shows a multi-dimensional characteristic, the measurements of the interfacial velocity and IAC by means of the double-sensor probe would become rather questionable. Consequently, a four-sensor probe method was proposed to overcome this difficulty by Kataoka et al. [22], and it has been used successfully to study the local characteristics and phase distribution of two-phase flow in a large diameter pipe [24–26].

The measurement principle of an optical fiber probe is based on the refraction and reflection laws. When the fiber tip is laid in a gas or liquid medium, the intensity of the reflected light is different due to the different refractive indexes of the two phases. This circumstance enables the probe to distinguish the existence of liquid or gas around the fiber tip. Therefore, the optical fiber can be used basically as a phase identifier for the two-phase mixture.

As illustrated in Fig. 1, a typical L-shaped four-sensor optical probe was mounted in the test pipe with its sensor tips facing vertically upward. The probe mainly consisted of four sensors that were made of optical fiber with a core diameter of 0.125 mm, each tip of which was shielded by a short stainless steel tube to prevent the sensor tips from deforming and deflecting from their original position in the flow. The fibers as well as the stainless steel tubes were bound to each other with high strength epoxy cement. The central front fiber, acted as the common sensor, was approximately 1 mm longer along the main flow direction than the other three rear independent sensors. The output signals from the common sensor and one of the other three can also be interpreted as coming from a double-sensor probe. Thus the four-sensor probe also represents a combination of three double-sensor probes. It is important to establish a three-dimensional Cartesian coordinate with its origin at the front sensor tip as shown in Fig. 1. The rear sensor tips of the four-sensor probe can be therefore denoted by (x_k, y_k, z_k), $k = 1$, 2, 3. In present study, the detailed coordinates of the four sensor tips are tabulated in Table 1. Based on these sensor tip coordinates, all the required geometrical parameters of the four-sensor probe can be obtained.

Because of the finite size of sensors and the time delay needed to wet or rewet the fiber tips, the output signal from the probe differs from an ideal square-wave. In order to regenerate the ideal square-wave signal, a threshold method proposed by Barrau et al. [29] was used to process the raw signal and to extract the required information of the two phases. Here the threshold voltage is defined as a certain value that is slight larger than the output voltage from a sensor when its tip is immersed in water only, thus the higher and lower voltages compared with the threshold could represent the gas phase and liquid phase, respectively. When different thresholds are selected in signal processing, different dwelling times of a given bubble that contacts with the sensor would be obtained, i.e. different void fractions would be yielded in a measurement. Then by comparing the cross-sectional averaged void fractions corresponding to these chosen thresholds with the reference value obtained from the other cross-calibration method, the most suitable threshold could be determined. Such a probe calibration should be undertaken for several typical flow conditions and thus an appropriate threshold can be obtained to ensure a reliable void fraction measurement for most flow conditions. As shown in Fig. 2, since the transient responses of the four sensors to the passage of a given bubble are nearly similar to each other, it is believed that the interfacial velocity measurement is comparatively insensitive to the choice of threshold. Accordingly, the threshold on the interfacial velocity measurement is selected to be the same as that on the void fraction measurement. The detailed verification of the

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