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Model of bubble velocity vector measurement in upward and downward bubbly two-phase flows using a four-sensor optical probe

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A B S T R A C T

The knowledge of bubble behaviors is of considerable significance for a proper understanding and modeling of two-phase flows. To obtain the information on the bubble motion, a novel model was developed, by which the bubble velocity vector can be directly calculated from six time intervals measured with a four-sensor probe. The measurements of local bubble velocity vector and void fraction were performed in both upward and downward bubbly flows by using a four-sensor optical probe. The area-averaged void fraction and bubble velocity obtained from the probe agree well with those measured by other cross-calibration methods, and the measurement errors are within 15% under various flow conditions. Experimental results of the bubble velocity vector reveal that the bubble lateral migration may be suppressed in upward flows, but be strengthened in downward flows as the liquid flow rate increases. Also, with an increase in gas flow rate, the bubble velocity distribution varies into the power−law profile in upward flows, but into an off-center peak profile in downward flows. In addition, the void fraction shows a core peak distribution at low void fraction for downward flows, but a wall peak distribution for upward flows. However, when the void fraction is relatively high, it displays an off-center peak distribution for downward flows but a core peak distribution for upward flows.

1. Introduction

Two-phase flow, as one of the most frequently encountered multiphase flows, has achieved an extensive application in practical industrial process, such as light water reactors, chemical plants, phase change heat exchangers and other industrial plants. To have a profound knowledge of two-phase flow, scholars have performed many investigations on the flow patterns, void fraction, friction pressure drop (Mishima and Ishii, 1984; Schlegel et al., 2010; Xing et al., 2014) as well as the local interfacial characteristics (Hibiki et al., 2001; Shen et al., 2006, 2012; Lucas et al., 2010; Smith et al., 2012; Tian et al., 2014a, b). Therein, the interfacial study plays an essential role in the model developments to describe and predict the transport of momentum, heat and mass (Ishii et al., 2001; Hibiki and Ishii, 2002; Nguyen et al., 2013).

In the past several decades, to obtain the local interfacial parameters of void fraction, interfacial area concentration (IAC) and interfacial velocity, various measurement methods have been developed (Hibiki et al., 1998; Sun et al., 2004; Ishii et al., 2004; Shen et al., 2005), like multi-sensor electrical and optical probe, video imaging techniques, laser Doppler anemometry (LDA), particle image velocimetry (PIV), etc. The video imaging, LDA and PIV methods, as the non-invasive technique for the measurement of a bubble interface, may be applicable only in low void fraction conditions, where the light could penetrate the system successfully. However, when the bubble number becomes relatively high, the light beam needs to cross large masses of interfaces to reach the video capture device and it is difficult to distinguish the interfaces due to bubbles overlapping severely. It is also unavailable when the system is operated at high temperature and high pressure and thus it can not be made of transparent materials. The multi-sensor probe, as one of the most promising techniques, has been widely employed to investigate the spatial distribution of local interfacial parameters in two-phase flow. Of the multi-sensor probes, the electrical probe utilizes the difference in the electrical conductivity between the liquid and gas phases, while the optical probe makes use of the difference in the refractive indexes between the two phases. In comparison with the conductivity probe, the optical probe can work well in conductive as well as in non-conductive

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Nomenclature

D	inner diameter of the pipe, m
D_0	basic determinant of four-sensor probe
D_k	directional determinant
J_L	superficial liquid velocity, m/s
J_G	superficial gas velocity, m/s
k	probe sensor tip No.
n	refractive index
N	bubble number
$\boldsymbol{n}_v$	unit vector in the bubble moving direction
r	distance between center and measurement location, m
R	reflection coefficient, or inner radius of pipe, m
$\boldsymbol{R}$	position vector, m
$\boldsymbol{S}$	distance vector, m
$\boldsymbol{V}$	bubble velocity vector, m/s
V_z	axial bubble velocity, m/s
V_r	radial bubble velocity, m/s
x_k, y_k, z_k	coordinates of the rear sensor tip of probe
z	axial distance from the inlet, m
Greek symbols	
α	void fraction, or polar angle, rad
β	azimuth angle, rad
Ω	total sampling time, s
$\Delta\tau$	dwelling time, s
Δt	time interval, s
Operators	
$< >$	area-averaged quantity

systems and has better signal-noise ratio. On the other hand, the presence of a liquid film on the sensor tip may reduce the effectiveness of the conductivity probe for the time delay needed to wet or dry the sensor tips, but has little influence on that of the optical probe. Consequently, the sensitivity of optical probe is higher than that of conductivity probe.

As one of two most common types of probes, the double-sensor probe, with its simple structure and easy fabrication, is utilized by most researchers to obtain the local parameters. Unfortunately, due to the problematic assumption for spherical bubble shape and one-dimensional interfacial motion, it was reported that the measured parameters such as the IAC obtained by means of the double-sensor probe may be not reliable, especially in a multi-dimensional two-phase flow (Shen et al., 2008). As a consequence, a four-sensor probe was designed to improve the measurements (Kataoka et al., 1986; Shen et al., 2005), and it has been used successfully to study the local characteristics and phase distribution of two-phase (Revankar and Ishii, 1993; Ishii and Kim, 2001; Hibiki et al., 2004; Shen et al., 2006; Tian et al., 2012). However, among all of these previous works, the interfacial velocity measured in axis was acted as the bubble velocity and this may be feasible in the conditions where the velocity of the gas bubbles is predominant in the axial direction. While under such conditions like downward, inclined, and large diameter pipe flows, where the bubble lateral motion prevails, the bubble movement is therefore not purely in the axial direction.

To characterize the flows more comprehensive, some attentions have been paid to the distributions of the mean axial, radial and azimuthal bubble velocities in a cross area of the pipe. Mishra et al. (2002) previously proposed a technique for measuring the bubble velocity vector of liquid droplets in oil-in-water multiphase flows by using a four-sensor probe. According to the interfacial measurement theorem, Shen et al. (2005) pointed out that the four-sensor probe is only able to measure the interfacial velocity component in the interfacial direction but can not measure the 3-D interfacial velocity vector without adding some special interfacial shape assumptions. Subsequently, Shen et al. (2008) established a method for measuring the local instantaneous interfacial velocity vector by using three independent four-sensor probes, while there are few available measurement results about this kind of probe method in open literature. Luther et al. (2004) and Guet et al. (2005) developed a model to reconstruct the aspect ratio and velocity of bubbles from output signals of the four-sensor probe. However, their data processing algorithm requires nonlinear optimization to obtain these variables. Additionally, Xue et al. (2008) proposed an algorithm for the determination of bubble size and velocity vector, which also need to be solved numerically and is not able to yield analytical solutions with four variables in three nonlinear equations.

It should be noted that the technique of Mishra et al. (2002) adopts an iterative solution methodology and yet yields no analytical solutions. To overcome this problem as well as some certain limitations reported in Mishra et al. (2002), such as the spherical shape assumption and the requirement of orthogonal arrangement for the four sensor tips, Lucas and Mishra (2005) derived a mathematical model, which can obtain an explicit expressions for unknowns on the velocity vector for a spherical or ellipsoid gas bubble. However, in this model, the unknown of azimuth angle β is finally calculated from the arc tangent function with a range from $-\pi/2$ to $\pi/2$, which can not completely represent the actual azimuth angle of a bubble with no inclination toward any direction in the plane vertical to the main flow. On the other hand, in the solution procedures of the polar angle α and the magnitude V of the bubble velocity, the obtained azimuth angle β is required. All of these issues may result in an unreliable bubble velocity vector measurement in flows. From this point of view, a novel improved mathematical model that is proposed in present study has successfully solved the above-mentioned problems reported in Mishra et al. (2002), Lucas and Mishra (2005), Lucas et al. (2011) and Lucas and Zhao (2013). Meanwhile, experiments on both the downward and upward two-phase flow were carried out with a four-sensor optical probe that was applied to measure the bubble velocity vector and other local interfacial parameters. A detailed discussion and comparison of the distribution of local parameters (include the polar angle, bubble velocity and void fraction) between the downward and upward flows were also performed.

2. Four-sensor optical probe and theoretical model

2.1. Optical probes measurement approach

The measurement principle of an optical probe is on the basis of the refraction and reflection laws. Since the core refractive index of silica fiber is 1.46, the theoretical reflection coefficients calculated by Eq. (1) for the water phase (the refractive index is 1.33) and air phase (the refractive index is 1.00) are 0.00217 and 0.0350, respectively.

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2, \quad (1)$$

where R is the reflection coefficient and n_1 and n_2 denote the refractive indexes of the two different types of media. As a result, when the fiber tip lays in a gas or liquid medium, the intensity of