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Local interfacial velocity measurement method using a four-sensor probe

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ABSTRACT

This paper presents a theoretical foundation of the measurement methods for the instantaneous local interfacial velocity vector and the time-averaged local interfacial area concentration using a four-sensor probe for multi-dimensional two-phase flow measurements. The measurement method is derived based on a large bubble assumption that locally views the front and rear interfaces of an approaching bubble as two tangent planes. The newly-derived method provides an explicit expression for the instantaneous local interfacial velocity vector using a four-sensor probe. The derived method for the time-averaged local interfacial area concentration was found to be in the same form as that proposed by Kataoka et al. (1986) [1]. The derived method was applied to the practical two-phase flow measurements in a vertical pipe with an inner diameter of 200 mm. The measured void fraction and interfacial velocity component in the axial direction were checked against the void fraction measurement using differential pressure gages and the superficial gas velocity measurement using gas flow meters, respectively. The measured interfacial velocity components in the radial and circumferential velocity components were found to be close to zero, which is in accordance with the fact that no stable flow of bubbles with certain horizontal velocity component exists in a vertical circular pipe. The measured interfacial area concentrations showed reasonable radial distributions in the pipe. The good agreements in the practical measurements suggest that the newly-derived method can reasonably measure interfacial velocity vector and interfacial area concentration in multi-dimensional two-phase flows.

1. Introduction

In order to develop or improve the models for describing and predicting the behavior of two-phase flow systems, it is fundamental to develop accurate instrumentation techniques for two-phase flow parameters measurements. Due to the success in pioneering work of Neal and Bankoff [2] and Miller and Mitchie [3] on conductivity and optical fiber probes, respectively, the phase discrimination probes have been widely utilized in two-phase flow studies as local measuring devices. For different purposes the probe with different number of sensors is often utilized in practical two-phase flow measurements. A single sensor probe is usually used for the local measurements of bubble frequency and void fraction. No important assumption on the bubble shape and bubble motion is necessary for the measurements. In order to measure bubbly/interfacial velocity, interfacial area concentration (IAC) and bubble size, many researchers [1,4–10] took multi-sensor probes in the bubbly flow measurement. The representatives of the multi-sensor probes are a double-sensor probe and a four-sensor probe. The double-sensor probe consists of a front sensor and a rear sensor. The four-sensor probe is composed of a central front sensor and three peripheral rear sensors. A typical four-sensor probe is shown in Fig. 1. It is impossible for a multi-sensor probe to measure interfacial velocity, interfacial area concentration and bubble size in a two-phase flow without adding any assumption on bubble shape or bubble motion. Existing measurement methods of multi-sensor probe are summarized in Table 1.

The interfacial velocity can be approximated in one-dimensional two-phase flow by using the ratio of two sensor tip separation to the time difference when an interface is passing the two sensor tips of a double-sensor probe. Kataoka et al. [1] and Hibiki et al. [4] assumed that the bubbles are in a spherical shape and move along the main flow with random transverse velocity components and developed a way for IAC measurement by using the double-sensor probe. So their methods are only valid for a one-dimensional bubbly flow full of approximate spherical bubbles.

Mishra et al. [8] assumed that the droplets are spherical in shape and proposed a computational scheme using the implicit expressions describing the spherical shape and the special configurations of the orthogonal four-sensor probe to calculate the

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Nomenclature

A	cross-sectional area of a pipe, m^2
A_0	determinant of a four-sensor probe
$A_{01,l}, A_{02,l}, A_{03,l}$	determinants relating to the l-th interface passed through a four-sensor probe
a_i	time-averaged interfacial area concentration (IAC), 1/m
D	inner diameter of a pipe, m
D_{sensor}	diameter of a optical fiber or an acupuncture needle, m
j_G	superficial gas velocity, m/s
j_L	superficial liquid velocity, m/s
N_i	detected interface number
$\mathbf{n}_{0k}$	unit vector of the distance vector, $\mathbf{s}_{0k}$, ($k = 1, 2, 3$)
$\mathbf{n}_{i,l}$	surface normal unit vector at a point on the l-th interface
$\mathbf{n}_{v,l}$	unit vector of the interfacial velocity vector, $\mathbf{V}_{i,l}$
R	inner radius of a pipe, m
R_1, R_2, R_3, R_∞	curvature radii of the l-th interface, m
r	radial distance, m
r_{rec}	receding interface ratio
r_{miss}	missing interface ratio
$\mathbf{s}_{0k}$	distance vector from the front sensor tip to the k-th rear sensor tip, m
s_{p12}	projected distance of the distance vector from the rear sensor tip, 1, to 2, in a vertical surface of a four-sensor probe, m
s_{p13}	projected distance of the distance vector from the rear sensor tip, 1, to 3, in a vertical surface of a four-sensor probe, m
s_{p23}	projected distance of the distance vector from the rear sensor tip, 2, to 3, in a vertical surface of a four-sensor probe, m
$t_{k,2h}, t_{k,2h+1}$	time when two interfaces of the h-th bubble pass through the k-th sensor ($k = 0, 1, 2, 3$), s
$t_{k,l}$	time when the l-th interface passes through the k-th sensor ($k = 0, 1, 2, 3$), s
$\mathbf{V}_{i,l}$	velocity vector of the l-th interface, m/s
V_{ix}	average value of all interfacial velocity components in the x direction, m/s
V_{iy}	average value of all interfacial velocity components in the y direction, m/s
V_{iz}	average value of all interfacial velocity components in the z direction, m/s
$V_{m0k,l}$	measurable velocity when the l-th interface moves from the front sensor tip, 0, to the rear sensor tip, k ($k = 1, 2, 3$), m/s
z	axial distance, m

Greek symbols

α	void fraction
$\langle\alpha\rangle$	area-averaged void fraction
$\delta t_{0k,l}$	time when the l-th interface immigrates from the front sensor tip to the k-th rear sensor tip, s
$\delta t_{k,h}$	residual time when the k-th sensor tip stays in the h-th bubble, s
$\eta_{x0k}, \eta_{y0k}, \eta_{z0k}$	angle between $\mathbf{s}_{0k}$ and x, y and z axis, respectively
$\eta_{xi,l}, \eta_{yi,l}, \eta_{zi,l}$	angle between $\mathbf{n}_{i,l}$ and x, y and z axis, respectively
$\eta_{xv,l}, \eta_{yv,l}, \eta_{zv,l}$	angle between $\mathbf{V}_{i,l}$ and x, y and z axis, respectively
Ω	time interval for averaging, s

Subscipts

0	front sensor of a four-sensor probe
1, 2, 3	the 1st, 2nd and 3rd rear sensor of a four-sensor probe
eff	effective bubbles or interfaces
h	the h-th bubble
k	the k-th rear sensor of a four-sensor probe, $k = 1, 2, 3$
l	the l-th interface
true	true value
x, y, z	x, y, and z axes

droplet velocity and diameter. Luther et al. [7] assumed the shape of the bubble is ellipsoidal and proposed a complicated model and algorithm, which has to be numerically solved using a constrained nonlinear least-square optimization, to measure the bubble's aspect ratio and its velocity. Xue et al. [9] assumed the bubbles are ellipsoidal and proposed to measure the IAC by numerically solving the basic equations describing the ellipsoidal shape, which is expressed by the geometrical sizes of four-sensor probe and the passing times of a bubble over the 4 sensor tips in a bubbly flow. All of these researchers could not propose explicit ways to measure the bubble or droplet velocity, bubble size and IAC. Their ways to obtain the velocity and other quantities have to be realized by using the iterative numerical calculation, whose complexity may limit the application of these methods to practical measurements.

Now the four-sensor probe is famous for its capability in the measurement of the local time-averaged IAC, which was first proposed by Kataoka et al. [1]. In deriving the measurement theory, Kataoka et al. [1] assumed that the probe size is considerably smaller than a bubble or drop diameter. The assumotion imposes a limitation on the application of the four-sensor probe to the small bubble measurement. Fortunately, the optical or conductivity four-sensor probe can be fabricated in a extremely size and it can be viewed to be considerably smaller than a bubble diameter in a practical bubbly flow. As a result of that, Revankar and Ishii [5] re-derived its IAC measurement theory and performed photographic benchmarks for the IAC measurement by using the cap bubbles in a two-phase flow. Kim et al. [10] photographically benchmarked the four-sensor probe measurement by using the stable slug bubbles in a two-phase flow. Shen et al. [6,11] improved its local time-averaged IAC measurement method by extending the measurement from the oncoming interfaces to the receding interfaces and proposed the basic principle for interfacial normal direction measurement by using a four-sensor probe. Although they derived the expression of the instantaneous local interfacial velocity vector component in the surface normal direction for the IAC measurement, they were not successful in further developing the measurement method for the instantaneous local interfacial velocity vector in 3D two-phase flow. Euh et al. [12] combined a four-sensor probe with a double-sensor probe into a five-sensor probe and increased the accuracy of the IAC measurement for missing bubbles, which touch the front sensor and miss one or more than one rear sensor(s) of a multi-sensor probe.

However, up to now there is no effective and explicit way to measure the local instantaneous 3-dimensional interfacial velocity vector by using a four-sensor probe in the 3-dimensional two-phase flow. The interfacial velocity is an important parameter to understand the flow structure and to model the 3-dimensional two-phase flow. To overcome the problem, this paper aims to develop a reliable explicit four-sensor probe measurement expression for the local instantaneous 3-dimensional interfacial velocity vector by using a large bubble assumption that locally views the front and rear interfaces of an approaching bubble as two tangent planes and to verify the reliability of the newly-developed method in the 3-dimensional two-phase flow.