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Error reduction, evaluation and correction for the intrusive optical four-sensor probe measurement in multi-dimensional two-phase flow

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Abstract

The objective of the present study is to increase the reliability of multi-dimensional two-phase flow measurement using an intrusive optical four-sensor probe. We investigated the error reducing ways in fabricating an optical conical four-sensor probe from its basic principles and sought for a control technique to sharpen the optical fiber tip and a sensor assembling method for a four-sensor probe. According to the measuring process by a multi-sensor probe, measurement errors were classified into signal processing errors and hydrodynamic errors. The signal processing errors in the void fraction due to the threshold setting and those in the interfacial area concentration (IAC) due to the interface-pairing scheme and the threshold setting were analyzed and concluded to be tiny and negligible in the measurement by an optical four-sensor probe. The hydrodynamic errors were classified into oncoming bubble errors, receding bubble errors and transversal or missing bubble errors according to the bubble motion relative to the probe. The maximum errors in both IAC and void fraction due to oncoming bubbles in a four-sensor probe measurement were estimated to be 10%. The maximum underestimation for IAC in the traditional transversal bubble recovering way of a four-sensor probe was reported up to 30% when the intensity of bubble velocity fluctuation equaled to 1 and the bubble size was close to the probe separations between sensor tips. The maximum measurement errors in IAC and void fraction for the receding bubbles were valued at 31% and 38%, respectively, at low liquid and high gas flow rates conditions by performing evaluation experiments using downward-facing and upward-facing probes. To overcome the unsatisfactory measurement errors for the receding and transversal bubbles, we proposed expressions for the correction of IAC and void fraction in the four-sensor probe measurement in a multi-dimensional two-phase flow by adding the contribution of escaped bubbles due to the hindrance of the probe rear parts and that of transversal bubbles due to the existence of finite distance separation between the sensor tips.

Keywords: Multi-dimensional two-phase flow; Four-sensor probe; Interfacial area concentration; Void fraction; Error reduction, evaluation and correction

1. Introduction

Local measurements are of primary importance in knowing the characteristics of two-phase flows. Due to the success in pioneering work of Neal and Bankoff [1] and Miller and Mitchie [2] on conductivity and optical fiber probes, respectively, the phase discrimination probe has been widely utilized in two-phase flow studies as a local measuring device.

The interfacial area concentration (IAC) is defined as the interfacial area existing in a unit volume of the mixture and specifies the geometric capability of interfacial transfer. The principle of IAC measurement with a double- or four-sensor probe was proposed originally by Kataoka et al. [3]. Hibiki et al. [4] improved the double-sensor probe method by assuming the probability density function (PDF) of the angle between the interfacial velocity vector and the mean flow direction vector in a quadratic function form of the

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Nomenclature

A	determinant
A_0	basic determinant of a four-sensor probe
a	time-averaged interfacial area concentration (IAC), 1/m
D	pipe inner diameter, m
D_0	fiber core diameter, m
D_b	bubble diameter, m
D_1	flat end diameter of the conical fiber tip, m
D_s	outer diameter of stainless steel pipe, m
f	bubble frequency, 1/s
H_{max}	intensity of bubble velocity fluctuation
I_i	intensity of the incident ray, b/s
I_r	intensity of the reflection ray, b/s
I_{tr}	transmitted ray intensity, b/s
j	superficial velocity, m/s
l	minimum distance between the centers of two rear sensor fibers, m
N	interface number
n	refractive index
R	reflection coefficients or inner radius of a pipe, m
r	bubble or interface ratio or radial distance, m
$\mathbf{s}$	distance vector between two sensor tips, m
s_r	radial distance between two sensor tips, m
s_z	axial length between two sensor tips, m
$\mathbf{V}_i$	interfacial velocity vector, m/s
$\mathbf{V}_m$	measurable velocity vector between different sensor tips, m/s
V_{th}	threshold voltage, V
z	axial distance, m

Greek symbols

α	time-averaged void fraction
$\langle\alpha\rangle$	area-averaged void fraction
β	sensor tip half angle, °
Δt	time difference, s
η	angle between the distance vector of two sensor tips and the axis, °
Ω	time interval for averaging, s

Subscripts

0	front sensor of a multi-sensor probe
1, 2, 3	the 1th, 2th and 3th rear sensor of a multi-sensor probe
a, b, c	the ath, bth and cth figure in Fig. 1
b	the bth bubble
c	optical fiber cladding
co	optical fiber core
DFP	downward-facing probe
down	downward-moving bubbles
eff	effective bubbles or interfaces
esc	escaped bubbles
f	liquid phase
g	gas phase
k	the kth rear sensor of a multi-sensor probe, $k = 1, 2, 3$
l	the lth interface
rec	receding bubbles relative to a probe
t	total
tran	transversal bubbles
true	true value
UFP	upward-facing probe
up	upward-moving bubbles
x, y, z	x, y, and z axes

angle instead of the constant PDF postulated by Kataoka et al. [3]. The improved double-sensor probe method can measure the IAC effectively in a one-dimensional two-phase flow. However, when it is applied to the measurement in a multi-dimensional two-phase flow, the improved method will become unreliable due to its two main assumptions: (1) the interfacial velocity can be approximated by using the ratio of two sensor tip separation and time difference when the interface passing the two sensor tips and (2) the bubble is spherical in shape. On the other hand, the four-sensor probe methodology [3,5] gives an accurate measurement of IAC in principle without imposing the assumption of the spherical bubble shape and one-dimensional motion of bubbles. The original four-sensor probe method [3] enabled effective measurements of the IAC in a one-dimensional two-phase flow [6,7], but it did not tell how to deal with receding interfaces (namely interfaces that touch the rear sensor tip(s) ahead of the front sensor tip) in a multi-dimensional two-phase flow measurement. To apply the four-sensor probe method to a multi-dimensional two-phase flow measurement, Shen et al. [5] derived the interfacial measurement theorem relating the local instantaneous interfacial velocity to local measurable velocities based on the vector triangle analysis and improved the four-sensor probe method. Using the improved four-sensor probe method, not only oncoming interfaces (namely interfaces that touch the front sensor tip ahead of all rear sensor tips) but also receding ones could be measurable.

It should be mentioned here that the following four assumptions were employed in the derivation of the four-sensor probe method on the interfacial shape and velocity during the interface-sensor touching process and probe size: (1) the effect of interfacial curvature is neglected by assuming that the interface is a continuous and non-deforming curved surface, (2) the orientation of the normal vector at a fixed point in the continuous and non-deforming curved