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Optimal design of a four-sensor probe system to measure the flow properties of the dispersed phase in bubbly air–water multiphase flows

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ABSTRACT

This paper presents a systematic investigation on the design and development of a four-sensor probe system to be used for air–water multiphase flow measurements. A mathematical model is presented which can be used to determine the optimum axial separation of the front sensor with respect to three rear sensors within a four sensor probe system. This system can be used to measure flow properties of the dispersed phase in bubbly air–water flows accurately. Paper also presents a sensitivity analysis to determine the minimum sampling frequency requirements in the data collection process, so that associated errors in various output parameters can be minimized, for the given values of sensors co-ordinates. A particularly novel feature of this paper is development of a unique digital signal processing scheme to enable the accurate computation of different flow characteristics.

This paper also presents validation of four-sensor probe measurements from a flow visualization and measurement system which relies on using two high speed cameras mounted orthogonally. The results obtained from validation experiments show very high degree of similarity in measured flow variables from the two systems. This indicates that the four-sensor probe system developed in this study can be used with confidence to measure parameters of a dispersed multiphase flow. The flow characteristics obtained from the four-sensor probe system when used in a multiphase flow system are also presented. The results indicate a unique flow pattern corresponding to bubbles of different sizes in air–water flows.

1. Introduction

Multiphase flows are fairly common in many chemical, mining and mechanical industries. Air–water flows are typical of multiphase flows where density difference between the dispersed phase and the continuous phase is quite large. The essential parameters in two-phase air–water bubbly flows include volume fraction distribution of the dispersed phase, interfacial area concentration and the bubble size distribution corresponding to the dispersed phase.

Conductivity probes are used widely to measure various flow characteristics of bubbly multiphase flows within pipelines [1–15]. Wu et al. [16] have shown that a dual-sensor probe can be used to measure the time averaged velocity and interfacial area concentration of the dispersed phase in air–water multiphase flows with reasonable accuracy. However dual-sensor probes, because of their very nature, can only estimate the axial bubble velocity. Hence the use of dual-sensor probes for measuring dispersed phase parameters in three dimensional multiphase flows is not recommended. This challenge was overcome by introduction of a four-sensor probe to enable measurements of velocity vector (magnitude and direction) of the dispersed phase in bubbly multiphase flows [1,2]. Mishra et al. [1] and Lucas et al. [2] have presented a theoretical model which is used to compute various flow properties corresponding to the dispersed phase in typical bubbly air–water flows using the time delay measurements from a four-sensor probe. The developed model is based on the following assumptions:-

1. The mathematical model is valid for spherical bubbles.
2. The impact of a bubble on the probe does not affect the bubble's velocity vector.
3. Bubbles do not get deformed during the process of interaction with sensors.

Fig. 1 shows a schematic diagram of a typical four-sensor probe and the motion of a bubble of radius R moving with velocity vector $\mathbf{V}$. The velocity vector can be represented mathematically as:-

$$\mathbf{V} = v(\sin\alpha\,\sin\beta\,\mathbf{i} + \sin\alpha\,\cos\beta\,\mathbf{j} + \cos\alpha\,\mathbf{k}) \tag{1}$$

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where v is velocity magnitude, α is polar angle between velocity vector and probe axis and β is an azimuthal angle for velocity vector. Lucas et al. [2] developed a detailed procedure to calculate polar angle α and azimuthal angle β of vertically rising bubble from time delay measurements made by the four-sensor probe. The corresponding equations are given below.

$$\tan\ \beta = \frac{((z_1/\delta t_{11}) - (z_2/\delta t_{22}))((y_1/\delta t_{11}) - (y_3/\delta t_{33})) - ((z_1/\delta t_{11}) - (z_3/\delta t_{33}))((y_1/\delta t_{11}) - (y_2/\delta t_{22}))}{((z_1/\delta t_{11}) - (z_2/\delta t_{22}))((x_1/\delta t_{11}) - (x_2/\delta t_{22})) - ((z_1/\delta t_{11}) - (z_2/\delta t_{22}))((x_1/\delta t_{11}) - (x_3/\delta t_{33}))} \quad (2)$$

$$\tan\ \alpha = \frac{((z_1/\delta t_{11}) - (z_2/\delta t_{22}))}{((x_1/\delta t_{11}) - (x_2/\delta t_{22}))\sin\beta - ((y_1/\delta t_{11}) - (y_2/\delta t_{22}))\cos\beta} \quad (3)$$

$$\frac{v\delta t_{ii}}{2} = x_i\ \sin\ \alpha\ \sin\ \beta + y_i\ \sin\ \alpha\ \cos\ \beta + z_i\ \cos\ \alpha \quad (4)$$

Velocity magnitude v can be calculated using Eq. (4), where δt_{ii} represents the time interval between the contacts of the front sensor and ith rear sensor with the bubble, x_i, y_i and z_i are coordinate of ith rear sensor with respect to front sensors. Mishra et al. [8] later extended this model to compute other parameters of interest i.e. D, μ and ϑ, where D is diameter of a bubble, μ is the polar angle corresponding to the point of contact of front sensor and ϑ is the azimuthal angle corresponding to the point of first contact of the front sensor as defined in Fig. 1C. Various geometric parameters corresponding to bubble size and the first point of contact on a bubble have been shown in Fig. 1C. The relevant equations are shown below.

$$\tan\ \vartheta = \frac{((z_1/A_{11}) - (z_3/A_{33}))((y_1/A_{11}) - (y_2/A_{22})) - ((z_1/A_{11}) - (z_2/A_{22}))((y_1/A_{11}) - (y_3/A_{33}))}{((z_1/A_{11}) - (z_2/A_{22}))((x_1/A_{11}) - (x_3/A_{33})) - ((z_1/A_{11}) - (z_3/\delta t_{33}))((x_1/A_{11}) - (x_2/A_{22}))} \quad (5)$$

$$\tan\ \mu = \frac{((z_2/A_{22}) - (z_1/A_{11}))}{((x_1/A_{11}) - (x_2/A_{22}))\ \sin\ \vartheta - ((y_1/A_{11}) - (y_2/A_{22}))\ \cos\ \vartheta} \quad (6)$$

Diameter of a bubble D can be calculated using Eq. (7), where $i = 1, 2$ and 3

$$\frac{A_{ii}}{D} = \sin\ \mu\ \sin\vartheta + \sin\ \mu\ \cos\ \vartheta + \cos\ \vartheta \quad (7)$$

Thus, using the above equations, most of the flow parameters corresponding to the dispersed phase in air-water multiphase flows can be measured. Above model shows that for accurate measurement of dispersed flow parameters, time delays must be measured accurately. The accurate measurement of the time delays can be affected by location of four sensors in a four probe system. Hence for accurate measurement of flow parameters of the dispersed phase, for a given flow condition, a four-sensor probe needs to have an optimum sensors configuration.

Wu et al. [16] investigated the effect of axial sensors' separation on accuracy of velocity measurement for spherical and elliptical bubbles in air–water flow using typical dual-sensor probes. Authors concluded that measurable velocity may approach infinity if the ratio of the sensors' separation to the diameter of measured bubbles was smaller than the maximum relative fluctuation of the bubble velocity. Wu et al. [16] therefore suggested using an axial sensors' separation which is greater than half of the bubble diameter for effective elimination of this singularity problem.

Corre et al. [17] suggested a non-dimensional sensor separation parameter (axial separation divided by bubble diameter) in the range of 0.6–1 for accurate velocity measurements. The above recommendations were based on numerical simulations and hence effects of all the parameters have not been explicitly included in the probe design. The criteria proposed, also do not take into account likely flow conditions. This paper presents the development of an analytical model to determine the sensors locations for accurate measurement of dispersed phase flow parameters in a wide variety of multiphase flow conditions. In addition this paper explores possible circuits and presents a novel digital signal processing scheme to maximize the accuracy of measurements using the four sensor probe system.

Nomenclature

i, j, k	unit vectors in x, y and z direction (probe coordinate system(m))
N	number of bubble striking sensor
$\hat{n}_i$	the unit vector in the direction of **r**
$\hat{n}_v$	the unit vector in the direction of **V**
r	position vector of point of first contact of bubble with sensor 0(m)
r	magnitude of **r** (m)
$\mathbf{r_1}$	position vector of point of first contact of bubble with sensor 1(m)
r_1	magnitude of **r** (m)
S	axial distance between the front and the rear sensor (m)
T	sampling time (s)
U_g	superficial velocities of gas (m/s)
U_w	superficial velocities of water (m/s)
V	velocity vector
V_{amp}	output voltage from op amp (V)
V_{in}	circuit input voltage (V)
V_{out}	circuit output voltage (V)
v	velocity magnitude (m/s)
v_r	radial velocity or the velocity at the Y-axis (m/s)
v_z	axial velocity or the velocity at the Z-axis (m/s)
v_θ	azimuthal velocity or the velocity at the X-axis (m/s)
x, y, z	probe coordinate (m)
x_1, x_2, x_3	x coordinates of sensor 1, 2 and 3 with respect to sensor 0 (m)
y_1, y_2, y_3	y coordinates of sensor 1, 2 and 3 with respect to sensor 0 (m)
z_1, z_2, z_3	z coordinates of sensor 1, 2 and 3 with respect to sensor 0 (m)
α	polar angle (°)
β	azimuthal angle (0)
δt_{0a}	time delays equal to zero (s)
δt_{0a}	time taken for bubble to cross the sensor 0 (s)
$\delta t_{1a}\delta t_{1b}$	time delay between first bubble contact with the sensor 0 and first and last bubble contacts respectively with sensor 1(s)
$\delta t_{2a}\delta t_{2b}$	time delay between first bubble contact with the sensor 0 and first and last bubble contacts respectively with sensor 2(s)