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Brief communication

A method for measuring local instantaneous interfacial velocity vector in multi-dimensional two-phase flow

Xiuzhong Shen [a], Kaichiro Mishima [a,*], Hideo Nakamura [b]

[a] *Research Reactor Institute, Kyoto University, Kumatori-cho, Sennan-gun, Osaka 590-0494, Japan*
[b] *Nuclear Safety Research Center, Japan Atomic Energy Agency, Tokai-mura, Ibaraki 319-1195, Japan*

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1. Introduction

The existence and change of an interface are one of the most important processes in two-phase flows and contribute significantly to the transport of momentum, heat and mass. The variation of an interface also plays a role in the generation of fluid friction losses and fluid induced noise. In order to understand the behavior of two-phase flow and to make a better application of the two-phase flow in various industrial fields it is therefore essential to study the interfaces, especially the interfacial velocity. Such interfacial studies have been performed by means of various methods like multi-sensor electrical or optical probe (Kataoka et al., 1986; Hibiki et al., 1998; Shen et al., 2005), ultrasonic Doppler (Murakawa et al., 2005), laser Doppler velocimetry (LDV) and particle image velocimetry (PIV) and their related photographic methods (Bachalo, 1994; Shen et al., 2002).

The ultrasonic Doppler, LDV or PIV and photographic methods can be used in the measurement of an interface when the bubble number or void fraction is very low. However, when the bubble number or the void fraction increases the sound or the light beam has to cross a vast number of interfaces to reach the measurement volume, which makes it difficult to distinguish the interfaces.

The multi-sensor electrical or optical probe is the first, in many instances, the only experimental technique to study the detailed spatial distribution of local variables in two-phase flows. It works on the basis of the time differences in which an interface moves from one sensor tip to another one, the time difference being primarily related to the interfacial velocity. By using very fine sensors placed in the two-phase flow and laser or electronics with servo-loop technique, it is possible to measure the instantaneous interfacial directions and velocities of fine scales and high frequencies, time-averaged void fraction, time-averaged interfacial area concentration, etc. Many researchers extensively studied the time-averaged void fraction and time-averaged interfacial area concentration in the bubbly flow by using multi-sensor probes in the past several decades (Kataoka et al., 1986; Hibiki et al., 1998). By imposing the assumption that the interfacial velocity can be estimated by using the ratio of the distance between two neighboring sensor tips and the time difference for the interface passing through the two sensor tips, Kataoka et al. (1986) and Hibiki et al. (1998) measured the local interfacial velocity and obtained the time-averaged interfacial area concentration in the one-dimensional two-phase flow by using the double-sensor and four-sensor probes. However, when the interfacial lateral motion prevails and the two-phase flow shows its multi-dimensional characteristics, the existence of the lateral motions makes the above interfacial velocity and interfacial area concentration measurements questionable. Recently Shen et al. (2005) derived the interfacial measurement theorem for multi-sensor probe by using vector analysis and pointed out that a four-sensor probe could measure the interfacial velocity component in the interfacial direction but could not measure the 3-D interfacial velocity vector in multi-dimensional two-phase flow without adding the special interfacial shape assumption such as spherical shape or ellipsoidal shape. Their theory enabled the interfacial area concentration measurement and the instantaneous interfacial direction measurement in multi-dimensional two-phase flow. And they did measure the interfacial area concentration and the interfacial direction in air–water two-phase flow in a vertical large-diameter pipe (Shen et al., 2005, 2006).

With the further application of the interfacial measurement theorem (Shen et al., 2005) to the multi-sensor

* Corresponding author. Tel.: +81 72 451 2449; fax: +81 72 451 2637.
E-mail address: mishima@rri.kyoto-u.ac.jp (K. Mishima).

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probes, the present study established a method for measuring the local instantaneous interfacial velocity vector in multi-dimensional two-phase flow by using three independent four-sensor probes. Since a five- or six-sensor probe includes a lot of four-sensor combinations by sharing its sensors and at least three independent four-sensor sets exists among each probe, it was concluded that the five- or six-sensor probe was able to measure the local instantaneous interfacial velocity vector in multi-dimensional two-phase flow. A practical application and verification of this method was performed in an air–water two-phase flow in a pool.

2. Interfacial measurement method

Prior to the derivation of the interfacial measurement theory, it should be mentioned here that the following four assumptions were adopted in the derivation of the interfacial velocity measurement 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 on the continuous and non-deforming curved surface is constant, (3) the velocity of the interface is constant, and (4) the four-sensor probe is small in size relative to bubbles.

When the hth bubble, which has two interfaces, the lth and $(l+1)$th, or the $2h$th and $(2h+1)$th, passes through two neighboring sensors, 0 and 1, among a multi-sensor probe, it produces two signal serials as shown in Fig. 1. These signal serials contain basically two types of information, namely (1) time difference between the phase identification points in the two sensors (Δt_{01l}) and (2) residence time of each phase of gas and liquid (Δt_{0h}). The former is utilized in the interfacial velocity measurement and the latter is in the void fraction measurement.

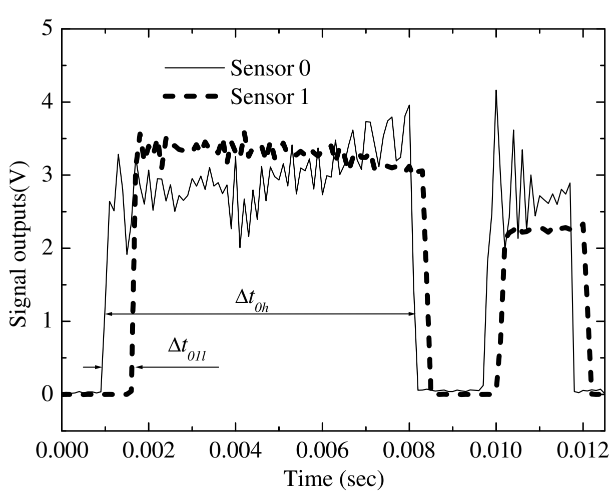


Fig. 1. Signal output when bubbles passes through two sensors.

2.1. Interfacial measurement theorem

In double-sensor probe and four-sensor probe measurements, we know the distance vector between two neighboring sensor tips and the time difference for the interface passing through the two sensor tips and can refer to the ratio of the distance vector and the time difference as the measurable interfacial velocity vector. In the process of four-sensor probe measurement improvement, Shen et al. (2005) analyzed the interfacial movement relative to a multi-sensor probe (see Fig. 2) and derived the interfacial measurement theorem for a multi-sensor probe measurement, which gives the general relation between the local instantaneous interfacial velocity vector and the local measurable interfacial velocity vectors. The derived interfacial measurement theorem tells us that all of the measurable interfacial velocity vectors in a fixed position on a surface have the same component in the surface normal direction and it also equals to the component of the local instantaneous interfacial velocity vector in the surface normal direction. The theorem can be expressed by

$$\mathbf{n}_{il} \cdot \mathbf{V}_{il} = \mathbf{n}_{il} \cdot \mathbf{V}_{m0kl} = V_{nl}, k = 1, 2, 3 \tag{1}$$

where $\mathbf{V}_{il}$ denotes the velocity vector of the lth interface passing through the point, $(\mathbf{x}_0, t_{0l})$ on the interface, at which the front sensor tip penetrates through the interface, and is defined by

$$\begin{aligned}\mathbf{V}_{il} &= V_{xil}\mathbf{i} + V_{yil}\mathbf{j} + V_{zil}\mathbf{k} \\ &= |\mathbf{V}_{il}|(\cos\eta_{xv}\mathbf{i} + \cos\eta_{yv}\mathbf{j} + \cos\eta_{zv}\mathbf{k}),\end{aligned} \tag{2}$$

$\mathbf{V}_{m0kl}$ stands for the measurable interfacial velocity vectors of the lth interface and is defined in terms of the distance vectors $\mathbf{s}_{0-k}$ from sensor tip 0 to k ($k = 1, 2, 3$) and the time difference when the lth interface moves from sensor tip 0 to k ($k = 1, 2, 3$) in the four-sensor probe, i.e.,

$$\mathbf{V}_{m0kl} = \frac{\mathbf{s}_{0-k}}{t_{kl} - t_{0l}}, \quad k = 1, 2, 3, \tag{3}$$

where the distance vectors $\mathbf{s}_{0-k}$ is given by

$$\mathbf{s}_{0-k} = |\mathbf{s}_{0-k}|(\cos\eta_{x0k}\mathbf{i} + \cos\eta_{y0k}\mathbf{j} + \cos\eta_{z0k}\mathbf{k}), \quad k = 1, 2, 3, \tag{4}$$

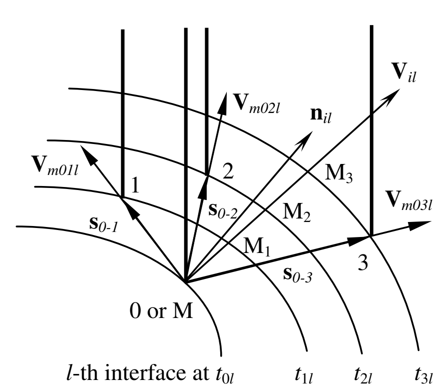


Fig. 2. Four-sensor probe and the lth interface.

$\mathbf{n}_{il}$ is the interfacial directional unit vector or the surface normal unit vector at $(\mathbf{x}_0, t_{0l})$ and is defined in terms of its 3 angles (shown in Fig. 3a),

$$\mathbf{n}_{il} = \cos\eta_{xi}\mathbf{i} + \cos\eta_{yi}\mathbf{j} + \cos\eta_{zi}\mathbf{k}, \tag{5}$$

and V_{nl} is the component of interfacial velocity vector in the surface normal direction at $(\mathbf{x}_0, t_{0l})$.

When the lateral motions of the interfaces exist in the two-phase flow, some interfaces crash into the probe on an oncoming way and some interfaces crash into the probe on a receding way. The oncoming interfaces will touch the front sensor tip, 0, ahead of the rear sensor tips, k, $(k = 1, 2, 3)$ and the receding interfaces will touch the rear sensor tips, k, $(k = 1, 2, 3)$ ahead of the front sensor tip, 0, in the measurement. Eq. (3) shows that direction of the measurable interfacial velocity vector is determined by the time difference when the lth interface moves from sensor tip 0 to k $(k = 1, 2, 3)$ in the four-sensor probe. The direction is positive, namely the same with the positive direction of the corresponding distance vector $\mathbf{s}_{0-k}$ from sensor tip 0 to k $(k = 1, 2, 3)$, for an oncoming interface and is negative, namely the same with the negative direction of the corresponding distance vector $\mathbf{s}_{0-k}$ from sensor tip k $(k = 1, 2, 3)$ to 0, for a receding interface.

2.2. Interfacial normal direction and interfacial velocity component in this direction

By applying the interfacial measurement theorem to a four-sensor probe, we can obtain the local instantaneous interfacial normal unit vector, $\mathbf{n}_{il}$, and the local instantaneous interfacial velocity component in the surface normal direction, $\mathbf{V}_{nl}$, at $(\mathbf{x}_0, t_{0l})$ on the lth interface, at which the front sensor tip penetrates through the interface. The results are shown as follows:

$$\cos\eta_{xi} = \frac{\pm|A_{01l}|}{\sqrt{A_{01l}^2 + A_{02l}^2 + A_{03l}^2}},$$
$$\cos\eta_{yi} = \frac{\pm|A_{02l}|}{\sqrt{A_{01l}^2 + A_{02l}^2 + A_{03l}^2}} \quad \text{and}$$
$$\cos\eta_{zi} = \frac{\pm|A_{03l}|}{\sqrt{A_{01l}^2 + A_{02l}^2 + A_{03l}^2}} \tag{6–8}$$

$$\mathbf{V}_{nl} = V_{nl}\cdot\mathbf{n}_{il} = \frac{A_0}{\sqrt{A_{01l}^2 + A_{02l}^2 + A_{03l}^2}}\cdot\mathbf{n}_{il}, \tag{9}$$

where A_{01l}, A_{02l} and A_{03l} are referred to as the directional determinants since they are decided by the distance vectors between the sensor tips among the four-sensor probe and the directions of the measurable interfacial velocity vector and are finally used to determine the interfacial direction. They are expressed by

$$A_{01l} = \begin{vmatrix} \frac{t_{1l}-t_{0l}}{|\mathbf{s}_{0-1}|} & \cos\eta_{y01} & \cos\eta_{z01} \\ \frac{t_{2l}-t_{0l}}{|\mathbf{s}_{0-2}|} & \cos\eta_{y02} & \cos\eta_{z02} \\ \frac{t_{3l}-t_{0l}}{|\mathbf{s}_{0-3}|} & \cos\eta_{y03} & \cos\eta_{z03} \end{vmatrix},$$
$$A_{02l} = \begin{vmatrix} \cos\eta_{x01} & \frac{t_{1l}-t_{0l}}{|\mathbf{s}_{0-1}|} & \cos\eta_{z01} \\ \cos\eta_{x02} & \frac{t_{2l}-t_{0l}}{|\mathbf{s}_{0-2}|} & \cos\eta_{z02} \\ \cos\eta_{x03} & \frac{t_{3l}-t_{0l}}{|\mathbf{s}_{0-3}|} & \cos\eta_{z03} \end{vmatrix} \quad \text{and}$$
$$A_{03l} = \begin{vmatrix} \cos\eta_{x01} & \cos\eta_{y01} & \frac{t_{1l}-t_{0l}}{|\mathbf{s}_{0-1}|} \\ \cos\eta_{x02} & \cos\eta_{y02} & \frac{t_{2l}-t_{0l}}{|\mathbf{s}_{0-2}|} \\ \cos\eta_{x03} & \cos\eta_{y03} & \frac{t_{3l}-t_{0l}}{|\mathbf{s}_{0-3}|} \end{vmatrix}. \tag{10–12}$$

A_0 is the basic determinant of a four-sensor probe which is determined by the geometrical configuration of the four-sensor probe. It is given by

$$A_0 = \begin{vmatrix} \cos\eta_{x01} & \cos\eta_{y01} & \cos\eta_{z01} \\ \cos\eta_{x02} & \cos\eta_{y02} & \cos\eta_{z02} \\ \cos\eta_{x03} & \cos\eta_{y03} & \cos\eta_{z03} \end{vmatrix}. \tag{13}$$

Since it is required in the four-sensor probe that the four-sensor tips should not be arranged in a same plane and the four sensors should be independent of each other, the basic determinant of the four-sensor probe should not equal to zero.

Due to the fact that there exist two surface normal directions, the outward and the inward, at any point on an interface, each of $\cos\eta_{xi}$, $\cos\eta_{yi}$ and $\cos\eta_{zi}$ in Eqs. (6)–(8) has 2 roots (positive and negative), which correspond to two complementary angles for each of η_{xi}, η_{yi} and η_{zi} in $[0, \pi]$. The positive cosine value stands for the acute angle and the negative cosine value for the obtuse angle. The two complementary angles for the oncoming and receding interfaces are shown in Fig. 3b and c, respectively, if η_{zi} is taken as an example. Note that the outward interfacial

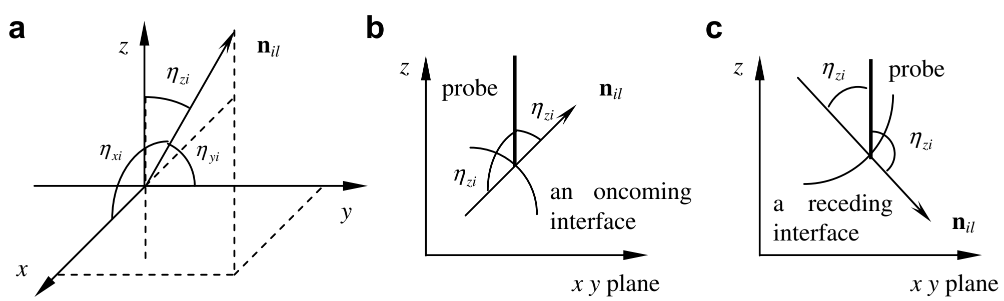


Fig. 3. Angles between $\mathbf{n}_i$ and the coordinate axes. (a) η_{xi}, η_{yi} and η_{xi}, (b) for an oncoming interface, (c) for a receding interface.

normal direction is usually chosen to be the positive interfacial direction and only one angle is a right solution for each interface. The positive or negative cosine value selection for each $\cos\eta_{xi}$, $\cos\eta_{yi}$ and $\cos\eta_{zi}$ in Eqs. (6)–(8) can be determined by the sign of A_{01l}, A_{02l} and A_{03l}, respectively. The direction of $\mathbf{V}_{nl}$ is identical to that of $\mathbf{n}_i$ on any interface.

Generally, if any sensor, k ($k = 0$ or 1 or 2 or 3) is chosen as the front sensor and the others the rear sensors, there exist four four-sensor probes in one four-sensor probe. Hence we can obtain four local instantaneous interfacial directional unit vectors, $\mathbf{n}_{ikl}$, $(k = 0,1,2,3)$, and four local instantaneous four interfacial velocity components in the normal direction, $\mathbf{V}_{nkl}\,(\mathbf{x}_k, t_{kl})$, $(k = 0,1,2,3)$, by extending Eqs. (6)–(9) to any of the four four-sensor probes. However, it can be theoretically proven that the four local instantaneous interfacial directional unit vectors, $\mathbf{n}_{ikl}$, $(k = 0,1,2,3)$ at different sensor tips are not independent and identical to each other, i.e.,

$$\mathbf{n}_{i0l} = \mathbf{n}_{i1l} = \mathbf{n}_{i2l} = \mathbf{n}_{i3l}. \tag{14}$$

And the four local instantaneous interfacial velocity components in the surface normal direction, $V_{nkl}(\mathbf{x}_k, t_{kl})$ $(k = 0,1,2,3)$, are also not independent and keep the same valve when the lth interface passing through the four-sensor probe, namely,

$$V_{n0l}(\mathbf{x}_0, t_{0l}) = V_{n1l}(\mathbf{x}_1, t_{1l}) = V_{n2l}(\mathbf{x}_2, t_{2l}) = V_{n3l}(\mathbf{x}_3, t_{3l}). \tag{15}$$

Eqs. (14) and (15) are the internal characteristics of a four-sensor probe when it is used in the interfacial measurement. Hence, any sensor, k ($k = 0$ or 1 or 2 or 3) of the four-sensor probe can be chosen as the front sensor and the others the rear sensors in the practical measurement of the local instantaneous interfacial directional unit vector and the local instantaneous interfacial velocity component in the surface normal direction.

2.3. Interfacial velocity vector measurement

The interfacial velocity vector includes three independent velocity components in x, y and z directions. Accordingly we need at least three equations to solve for the interfacial velocity vector in the interfacial measurement. If we can apply three independent four-sensor probes to measure the same interface at three different positions (shown in Fig. 4), each probe gets an independent local instantaneous interfacial normal unit vector and an independent local instantaneous interfacial velocity component in surface normal direction. Since the velocity of an interface is assumed to be constant in the interface-sensor touching process, we can theoretically obtain the local instantaneous interfacial velocity vector for the lth interface by solving three independent equations from the application of the interfacial measurement theorem to the interface-sensor touching process in the three four-sensor probe measurement. In the measurement one of the four-sensor probes is chosen as the main probe and the other two are auxiliary.

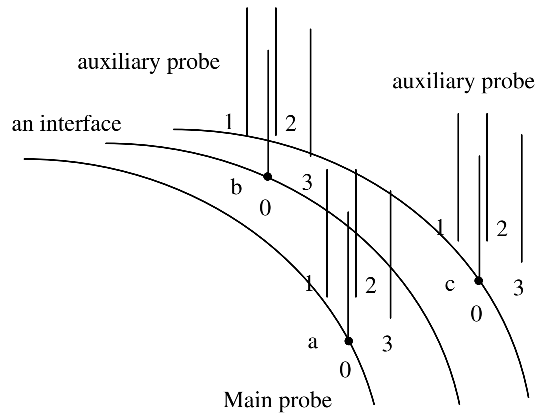


Fig. 4. Three four-sensor probes and an interface.

Now we will talk about the detailed derivation of the above consideration here. Similar to the previous development in Section 2.2, we can obtain the local instantaneous interfacial normal unit vectors $\mathbf{n}_{ipl}(\mathbf{x}_p, t_{pl})$, $(p = a,b,c)$ and the local instantaneous interfacial velocity components in the surface normal direction $V_{npl}(\mathbf{x}_p, t_{pl})$, $(p = a,b,c)$, by applying the interfacial measurement theorem to the interface-sensor touching process in the three four-sensor probe measurements at three independent points, a, b and c, respectively, on the interface (shown in Fig. 4). The $\mathbf{n}_{ipl}(\mathbf{x}_p, t_{pl})$ and $V_{npl}(\mathbf{x}_p, t_{pl})$ are expressed, respectively, by

$$\mathbf{n}_{ipl} = \cos\eta_{pxi}\mathbf{i} + \cos\eta_{pyi}\mathbf{j} + \cos\eta_{pzi}\mathbf{k}, \quad (p = a,b,c). \tag{16}$$

$$V_{npl}(\mathbf{x}_p, t_{pl}) = \frac{A_{p0}}{\sqrt{A_{p01l}^2 + A_{p02l}^2 + A_{p03l}^2}}, \quad (p = a,b,c), \tag{17}$$

where $\cos\eta_{pxi}$, $\cos\eta_{pyi}$ and $\cos\eta_{pzi}$, $(p = a,b,c)$, are similar to those in Eqs (6)–(8), respectively, A_{p01l}, A_{p02l}, and A_{p03l}, $(p = a,b,c)$, are the directional determinants similar to those in Eqs. (10)–(12), respectively, and A_{p0}, $(p = a,b,c)$, are the basic determinants similar to Eq. (13), when the pth four-sensor probe, $(p = a,b,c)$, is chosen.

In order to know the local instantaneous interfacial velocity vector for the lth interface, the interfacial measurement theorem is utilized again at the 3 points, $(\mathbf{x}_p, t_{pl})$, $(p = a,b,c)$, respectively, and the following 3 equations can be accordingly obtained. They form a linear equation set as follows:

$$\mathbf{n}_{ial}(\mathbf{x}_a, t_{al}) \cdot \mathbf{V}_{ial}(\mathbf{x}_a, t_{al}) = V_{nal}(\mathbf{x}_a, t_{al}), \tag{18}$$

$$\mathbf{n}_{ibl}(\mathbf{x}_b, t_{bl}) \cdot \mathbf{V}_{ibl}(\mathbf{x}_b, t_{bl}) = V_{nbl}(\mathbf{x}_b, t_{bl}), \tag{19}$$

$$\mathbf{n}_{icl}(\mathbf{x}_c, t_{cl}) \cdot \mathbf{V}_{icl}(\mathbf{x}_c, t_{cl}) = V_{ncl}(\mathbf{x}_c, t_{cl}), \tag{20}$$

where $\mathbf{V}_{ipl}(\mathbf{x}_p, t_{pl})$, $(p = a,b,c)$, are the local instantaneous interfacial velocity vectors at $(\mathbf{x}_p,\ t_{pl})$, $(p = a,b,c)$ for the lth interface.

The probe at $\mathbf{x}_a$ is chosen as the main probe and the two other probes at $\mathbf{x}_b$ and $\mathbf{x}_c$ are the auxiliary probes. Since we assumed that the interfacial velocity vector is constant in the interface-sensor touching process, the above three local instantaneous interfacial velocity vectors, $\mathbf{V}_{ipl}(\mathbf{x}_p, t_{pl})$, $(p = a, b, c)$, are the same with each other, i.e.,

$$\mathbf{V}_{ipl}(\mathbf{x}_p, t_{pl}) = \mathbf{V}_{il}, (p = a, b, c), \tag{21}$$

where $\mathbf{V}_{il}$ represents the local instantaneous interfacial velocity vector of the lth interface and is expressed in Eq. (2).

If the set of linear Eqs. (18)–(20) does not degenerate and $\Delta \neq 0$, we can obtain their unique solution of $\mathbf{V}_{il}$ according to Cramer's rule,

$$V_{xil} = \frac{\Delta_x}{\Delta}, \; V_{yil} = \frac{\Delta_y}{\Delta} \quad \text{and} \quad V_{zil} = \frac{\Delta_z}{\Delta} \qquad (22)–(24)$$

where

$$\Delta = \begin{vmatrix} A_{a01l} & A_{a02l} & A_{a03l} \\ A_{b01l} & A_{b02l} & A_{b03l} \\ A_{c01l} & A_{c02l} & A_{c03l} \end{vmatrix} \tag{25}$$

$$\Delta_x = \begin{vmatrix} A_{a0} & A_{a02l} & A_{a03l} \\ A_{b0} & A_{b02l} & A_{b03l} \\ A_{c0} & A_{c02l} & A_{c03l} \end{vmatrix},$$

$$\Delta_y = \begin{vmatrix} A_{a01l} & A_{a0} & A_{a03l} \\ A_{b01l} & A_{b0} & A_{b03l} \\ A_{c01l} & A_{c0} & A_{c03l} \end{vmatrix} \quad \text{and}$$

$$\Delta_z = \begin{vmatrix} A_{a01l} & A_{a02l} & A_{a0} \\ A_{b01l} & A_{b02l} & A_{b0} \\ A_{c01l} & A_{c02l} & A_{c0} \end{vmatrix} \qquad (26)–(28)$$

The magnitude of $\mathbf{V}_{il}$ is

$$|\mathbf{V}_{il}| = \frac{\sqrt{\Delta_x^2 + \Delta_y^2 + \Delta_z^2}}{|\Delta|}. \tag{29}$$

And the direction of $\mathbf{V}_{il}$ is

$$\cos\eta_{xv} = \frac{\Delta_x}{\sqrt{\Delta_x^2 + \Delta_y^2 + \Delta_z^2}},$$

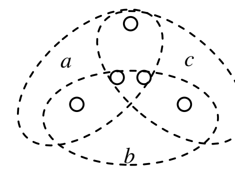
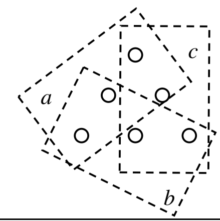
$$\cos\eta_{yv} = \frac{\Delta_y}{\sqrt{\Delta_x^2 + \Delta_y^2 + \Delta_z^2}} \quad \text{and}$$

$$\cos\eta_{zv} = \frac{\Delta_z}{\sqrt{\Delta_x^2 + \Delta_y^2 + \Delta_z^2}}. \qquad (30)–(32)$$

2.4. Feasible multi-sensor probes

The above-mentioned interfacial velocity measurement method with three independent four-sensor probes needs 12 sensors totally. The basic requirement for the three four-sensor probes is that the measured local instantaneous $\mathbf{n}_{ipl}(\mathbf{x}_p, t_{pl})$ and $V_{npl}(\mathbf{x}_p, t_{pl})$, $(p = a, b, c)$, from each probe should be independent of those from the other probes when an interface passes through the three probes. In view of this point, we can share the sensors among a multi-sensor probe to obtain three independent four-sensor probes. Although we can not get three independent four-sensor probes in one four-sensor probe, there exist 5 and 15 independent four-sensor probes in five- and six-sensor probes, respectively, as shown in Table 1. Therefore the corresponding numbers of three four-sensor probe set in five- and six-sensor probes are 10 $(= C_5^3)$ and 455 $(= C_{15}^3)$, respectively. When we select a set of the three four-sensor probes in a multi-sensor probe, we have to consider the relative position among the three probes to ensure that the measured local instantaneous $\mathbf{n}_{ipl}(\mathbf{x}_p, t_{pl})$ and $V_{npl}(\mathbf{x}_p, t_{pl})$, $(p = a, b, c)$, from each probe are different from those of the other two. To facilitate the readers to utilize the multi-sensor probe, we recommended one set of three four-sensor probes, a, b and c, for each of the five- and six-sensor probes in Table 1. Of course, there exists the requirement that the basic determinant of each four-sensor probe among the five- or six-sensor probe should not equal to zero.

Table 1
Multi-sensor probes and their three four-sensor probe sets

Multi-sensor probe	Total number of including four-sensor probe	Recommended three four-sensor probe sets
Four-sensor probe	$C_4^4 = 1$	No
Five-sensor probe	$C_5^4 = 5$	
Six-sensor probe	$C_6^4 = 15$	

3. Experiment

In order to investigate the practicability of this method, we measured the local instantaneous interfacial velocity vector in a two-phase flow by utilizing a six-sensor optical probe. The two-phase flow experiment is performed in pool and its experimental apparatus is shown in Fig. 5. The pool pipe is 1.2 m in height (L) and 50 mm in inner diameter (D). The air flows into the pipe through an injector with 0.5 mm in inner diameter. The inlet air flow rate and pressure were measured with a rotameter and a manometer, respectively. The measurement errors of the rotameter and the manometer are within ±0.5 % and ±0.3 %, respectively. The probe is arranged at point A at the heights of $L/D = 16.7$. Its radial measuring points are located at $r/R = 0$, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8 and 0.9. The photo and the configuration of the used six-sensor probe including the

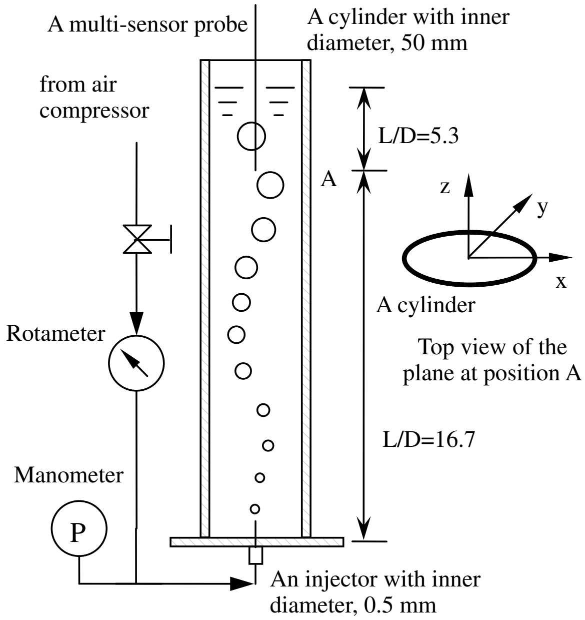


Fig. 5. Schematic of the pooling experiment.

coordinates of its six sensor tips (0, 1, 2, 3, 4 and 5) are illustrated in Fig. 6. The sampling frequency of the probe measuring system is 10 kHz.

The local instantaneous interfacial velocities obtained from the six-sensor probe measurement were summarized into the local average interfacial velocities and the standard deviations according to statistic analysis. The average values of the three interfacial velocity components are defined by

$$\overline{V_{xi}} = \frac{1}{N_i}\sum_{l=0}^{N_i-1} V_{xil},\quad \overline{V_{yi}} = \frac{1}{N_i}\sum_{l=0}^{N_i-1} V_{yil} \quad \text{and} \quad \overline{V_{zi}} = \frac{1}{N_i}\sum_{l=0}^{N_i-1} V_{zil}, \tag{33)–(35}$$

and their corresponding standard deviations are

$$V_{xi\_\text{sdev}} = \sqrt{\frac{1}{N_i}\sum_{l=0}^{N_i-1}(V_{xil}-\overline{V_{xi}})^2},$$
$$V_{yi\_\text{sdev}} = \sqrt{\frac{1}{N_i}\sum_{l=0}^{N_i-1}(V_{yil}-\overline{V_{yi}})^2},$$
$$V_{zi\_\text{sdev}} = \sqrt{\frac{1}{N_i}\sum_{l=0}^{N_i-1}(V_{zil}-\overline{V_{zi}})^2}. \tag{36)–(38}$$

where N_i is the measured interfacial number detected by the six-sensor probe.

The measured local average interfacial velocities, ($\overline{V_{xi}}$, $\overline{V_{yi}}$ and $\overline{V_{zi}}$), and their standard deviations, (V_{xi_sdev}, V_{yi_sdev} and V_{zi_sdev}), are shown in the right and left figures of Fig. 7, respectively, when $\langle j_l\rangle = 0.0$ m/s and $\langle j_g\rangle = 0.0256$ m/s. The measured area-averaged void fraction, $\langle\alpha\rangle$, reaches 0.113 at this flow condition. The average number of the detected bubble is about 3×1159 at each radial measuring point during the sampling time of 3×100 seconds. The measured results show that the secondary flows are prevailing and the bubbles move violently in the lateral direction in the pool. The interfacial velocity results also reveal that the $\overline{V_{yi}}$ and its variance are larger than the $\overline{V_{xi}}$ and its variance. It tells us that the circumferential movement of the bubbly secondary flow is much more violent than its radial movement in the pool.

The cross-sectional area-averaged superficial gas velocity is defined by

$$\langle j_g\rangle = \frac{1}{A}\int \alpha\overline{V_{zi}}\,\mathrm{d}A = \frac{1}{R^2}\int_0^R \alpha\overline{V_{zi}}2r\,\mathrm{d}r. \tag{39}$$

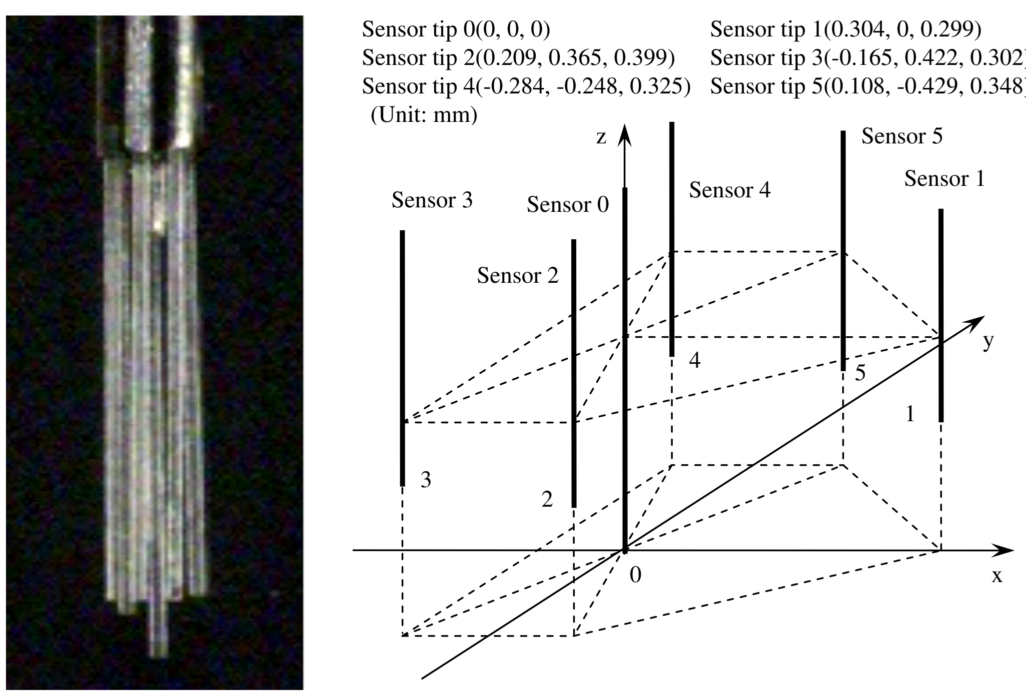


Fig. 6. Photo and configuration of the used six-sensor probe.

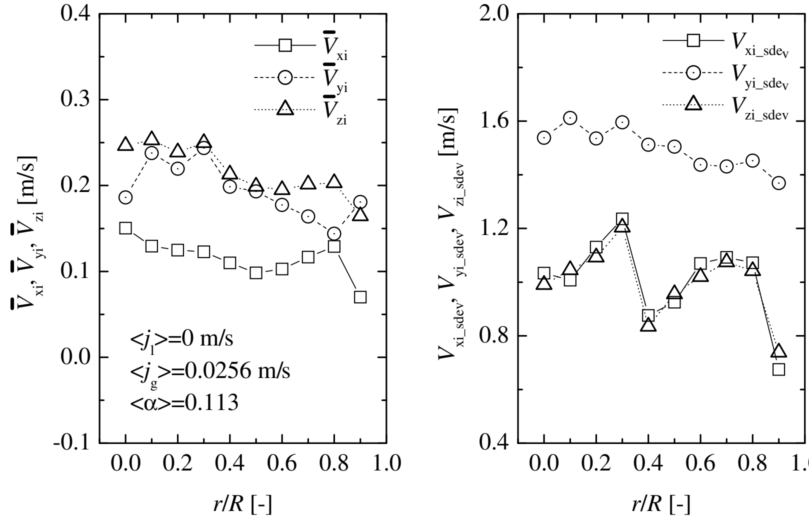


Fig. 7. Local average interfacial velocities and their standard deviation when $\langle j_l\rangle = 0.0$ m/s and $\langle j_g\rangle = 0.0256$ m/s.

Since the local void fraction, α, and the local interfacial velocity component in z direction, $\overline{V_{zi}}$, can be obtained from the six-sensor probe measurement we can obtain the $\langle j_g\rangle$. The $\langle j_g\rangle$ can also be measured from the rotameter measurement. Thus we can check the six-sensor probe measurement against the rotameter measurement. The comparing experiments were performed in the range of $\langle j_l\rangle = 0.0$ m/s, $\langle j_g\rangle = 0.00568$–$0.0327$ m/s and $\langle\alpha\rangle = 0.0256$–$0.177$. The comparisons are illustrated in Fig. 8. The agreement between the two measurements is fairly good. The measurement error decreases with the increase of the $\langle j_g\rangle$ and the $\langle\alpha\rangle$ in the pool. The maximum error is 17.9% and happens in the low $\langle j_g\rangle$ and low $\langle\alpha\rangle$ flow. The error can be attributed to the increase of the bubble escape effect due to the probe intrusiveness in the low $\langle j_g\rangle$ and low $\langle\alpha\rangle$ flow in the pool. Since the existence of the net liquid flow can greatly reduce this effect, we can predict that the present interfacial velocity vector measurement method can be successfully applied in the two-phase flow with net liquid flow.

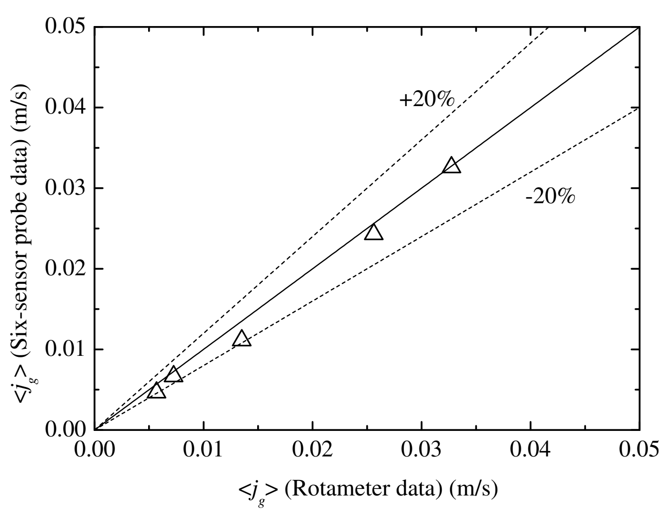


Fig. 8. Comparison between the six-sensor probe measurement and the rotameter measurement.

4. Summary and conclusion

By applying the interfacial measurement theorem to three independent four-sensor probes, this paper presented a theoretical formulation for the local measurement of the instantaneous interfacial velocity in multi-dimensional two-phase flow. By sharing the sensors of three four-sensor probes, we simplified the three probes into a five-sensor probe or a six-sensor probe. A six-sensor probe was manufactured and applied to the practical measurement of the local instantaneous interfacial velocity vector in multi-dimensional two-phase flow in a pool. Based on the measured local interfacial velocities and void fractions from the six-sensor probe measurement, we integrated them into the area-averaged superficial gas velocity over the cross-section, $\langle j_g\rangle$. The $\langle j_g\rangle$ obtained from the six-sensor probe measurement compared very well with that from the rotameter measurement. The concordance established the operational reliability of the five-sensor probe or six-sensor probe to measure the local instantaneous interfacial velocity vector in multi-dimensional two-phase flow.

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References

Bachalo, W.D., 1994. Experimental methods in multiphase flows. Int. J. Multiphase Flow 20, 261–295.

Hibiki, T., Hogsett, T., Ishii, M., 1998. Local measurement of interfacial area, interfacial velocity and turbulence in two-phase flow. J. Nucl. Eng. Des. 184, 287–304.

Kataoka, I., Ishii, M., Serizawa, A., 1986. Local formulation and measurements of interfacial area concentration in two-phase flow. Int. J. Multiphase Flow 12, 505–529.

Murakawa, H., Kikura, H., Aritomi, M., 2005. Application of ultrasonic doppler method for bubbly flow measurement using two ultrasonic frequencies. Exp. Therm. Fluid. Sci. 29, 843–850.

Shen, X., Yu, P., Yang, G., 2002. Hydromechanical investigation on 3 PWR upper plenum core structures. J. Nucl. Eng. Des. 217, 103–110.

Shen, X., Saito, Y., Mishima, K., Nakamura, H., 2005. Methodological improvement of an intrusive four-sensor probe for the multi-dimensional two-phase flow measurement. Int. J. Multiphase Flow 31, 593–617.

Shen, X., Saito, Y., Mishima, K., Nakamura, H., 2006. A study on the characteristics of upward air–water two-phase flow in a large pipe. Exp. Therm. Fluid Sci. 31, 21–36.