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Measuring Method for a Time-Averaged Multi-Dimensional Bubble Velocity by Using a Multi-Sensor Probe

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1. Introduction

A multi-dimensional behavior of a two-phase flow is important for the thermal hydraulic safety of a nuclear reactor and for the development of a system analysis code and a local CFD code. A rational model for an interfacial transfer of momentum and energy significantly affects the results of a two-phase flow analysis, which is closely related to the structure and motion of an interface. However, it is difficult to measure the information such as the interfacial area concentration and bubble velocity vector since the motion and geometry of the interface are very complicated. The multi-sensor probe method can measure the interfacial structure. A four-sensor probe method measures the interfacial area concentration by measuring the interface velocities of the sensor tips from the reference sensor tip[1]. Shen et al.(2005) derived a mathematical formula for the interfacial velocity for an interface's normal direction in the four-sensor method. However, they could not measure the interface velocity vector.[2] Shen et al.(2006) developed a new method for the local instantaneous multi-dimensional interface velocity vector by using six sensors composed of three four-sensor sets.[3] However, the method is very complicated for an application. For the flow analysis, the average velocity at a local point is more important than the instantaneous velocity. In this study, we developed a method to obtain the time-averaged bubble velocity vector by using only four sensors and by introducing some assumptions.

2. Four-Sensor Probe Method to Measure a Local Time-Averaged Multi-Dimensional Velocity

We focused on an average velocity rather than an instantaneous velocity. The interface normal vector at the local point, where the reference sensor tip is located, has a random direction even for a purely one-dimensional flow. However, in most two-phase flow conditions, the interface normal vectors can be considered to be symmetrically distributed in a bubble moving coordinate. The applied assumptions in this method are summarized as follows:

i) The time-averaged direction of interface normal vectors is the same as that of velocity vector.
ii) The curvature of the interface is negligible for the dimension of the scale of the configuration of the sensor tips
iii) Interface motion and geometry is not changed during the passage of the sensor tips.

In the following, we will derive the average bubble velocity vector by using measurable velocity data from four-sensors. Each parameter corresponds to a time-averaged variable. Under the assumption that time-averaged interface normal vector is the same as the unit velocity vector, Fig. 1 shows a relation between the average bubble velocity vector and the measured velocities in the direction of the sensors from the reference sensor. From Fig. 1(a), we can derive the following relation:

$$\left(\vec{V}_{p1}-\vec{V}_i\right)\cdot\vec{V}_i=0 \quad (1)$$

By applying the same approach to the other two sensors, following relations can be obtained.

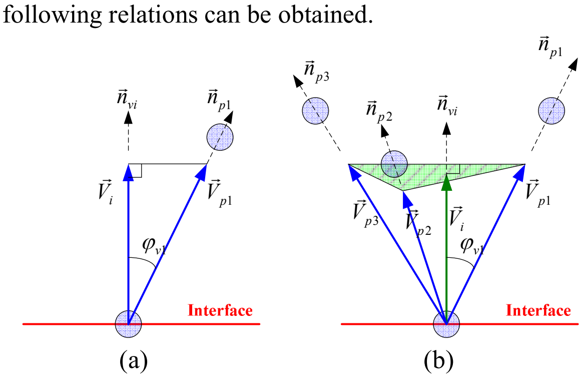

Fig. 1. Diagram to obtain a average interface velocity vector

$$\begin{aligned}
V_{p1x}V_{ix}+V_{p1y}V_{iy}+V_{p1z}V_{iz}&=\left|\vec{V}_i\right|^2\\
V_{p2x}V_{ix}+V_{p2y}V_{iy}+V_{p2z}V_{iz}&=\left|\vec{V}_i\right|^2\\
V_{p3x}V_{ix}+V_{p3y}V_{iy}+V_{p3z}V_{iz}&=\left|\vec{V}_i\right|^2
\end{aligned} \quad (2)$$

The solution of the above equation set is as follows:

$$|V_i| = \frac{|A_0'|}{\sqrt{A_1'^2 + A_2'^2 + A_3'^2}}, V_{ix} = \frac{A_0' A_1'}{A_1'^2 + A_2'^2 + A_3'^2} \quad (3)$$

$$, V_{iy} = \frac{A_0' A_2'}{A_1'^2 + A_2'^2 + A_3'^2}, V_{iz} = \frac{A_0' A_3'}{A_1'^2 + A_2'^2 + A_3'^2}$$

where

$$A_0' \equiv \begin{vmatrix} V_{p1x} & V_{p1y} & V_{p1x} \\ V_{p2x} & V_{p2y} & V_{p2z} \\ V_{p3x} & V_{p3y} & V_{p3z} \end{vmatrix}, \quad A_1' \equiv \begin{vmatrix} 1 & V_{p1y} & V_{p1x} \\ 1 & V_{p2y} & V_{p2z} \\ 1 & V_{p3y} & V_{p3z} \end{vmatrix},$$

$$A_2' \equiv \begin{vmatrix} V_{p1x} & 1 & V_{p1x} \\ V_{p2x} & 1 & V_{p2z} \\ V_{p3x} & 1 & V_{p3z} \end{vmatrix}, \quad A_3' \equiv \begin{vmatrix} V_{p1x} & V_{p1y} & 1 \\ V_{p2x} & V_{p2y} & 1 \\ V_{p3x} & V_{p3y} & 1 \end{vmatrix}$$

The above solutions can also be expressed as:

$$|V_i| = \frac{|A_0|}{\sqrt{A_1^2 + A_2^2 + A_3^2}}$$

$$\cos\eta_{vx} = \frac{A_1}{\sqrt{A_1^2 + A_2^2 + A_3^2}} \frac{A_0}{|A_0|}, \quad (4)$$

$$\cos\eta_{vy} = \frac{A_2}{\sqrt{A_1^2 + A_2^2 + A_3^2}} \frac{A_0}{|A_0|},$$

$$\cos\eta_{vz} = \frac{A_3}{\sqrt{A_1^2 + A_2^2 + A_3^2}} \frac{A_0}{|A_0|}$$

Where

$$A_0 \equiv \begin{vmatrix} \cos\eta_{p1x} & \cos\eta_{p1y} & \cos\eta_{p1x} \\ \cos\eta_{p2x} & \cos\eta_{p2y} & \cos\eta_{p2z} \\ \cos\eta_{p3x} & \cos\eta_{p3y} & \cos\eta_{p3z} \end{vmatrix}, A_1 \equiv \begin{vmatrix} 1/V_{p1} & \cos\eta_{p1y} & \cos\eta_{p1x} \\ 1/V_{p1} & \cos\eta_{p2y} & \cos\eta_{p2z} \\ 1/V_{p1} & \cos\eta_{p3y} & \cos\eta_{p3z} \end{vmatrix},$$

$$A_2 \equiv \begin{vmatrix} \cos\eta_{p1x} & 1/V_{p2} & \cos\eta_{p1x} \\ \cos\eta_{p2x} & 1/V_{p2} & \cos\eta_{p2z} \\ \cos\eta_{p3x} & 1/V_{p2} & \cos\eta_{p3z} \end{vmatrix}, A_3 \equiv \begin{vmatrix} \cos\eta_{p1x} & \cos\eta_{p1y} & 1/V_{p3} \\ \cos\eta_{p2x} & \cos\eta_{p2y} & 1/V_{p3} \\ \cos\eta_{p3x} & \cos\eta_{p3y} & 1/V_{p3} \end{vmatrix}$$

The various variables related to angles are summarized as follows:

η_{vx}, η_{vy}, η_{vz}: Unknown angles between average bubble velocity vector and each axis of coordinate.

η_{pkx}, η_{pky}, η_{pkz}: Known angles between each sensor tip from reference sensor and each axis of coordinate.(k=1,2,3)

3. Application

The developed method was applied to the DOBO experiment to obtain a local time-averaged multi-dimensional steam velocity. Figure 2 shows one of the results for the steam velocities, which agrees well with the visualization.

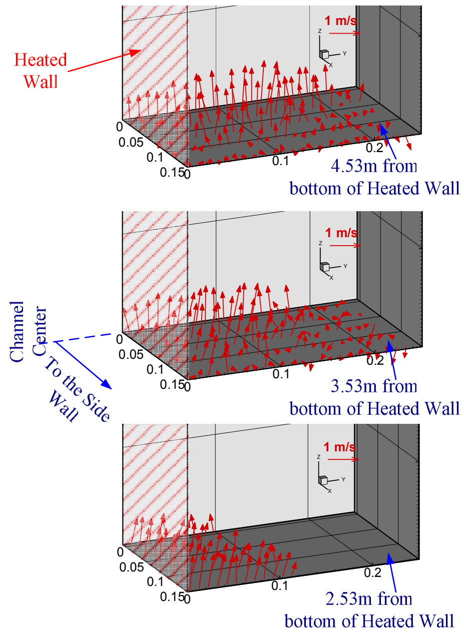

Fig. 2. Multi-dimensional steam velocity of DOBO experiment

4. Concluding Remarks

In this study, a methodology to obtain the average bubble velocity vector by using a four-sensor probe was established. The method has an advantage that it is simple and can be easily applied to a multi-dimensional flow. As a further study, an evaluation for the method will be performed with numerical and photographic methods.

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