Measurement of Two-dimensional Bubble Velocity by Using Tri-fiber-optical Probe

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Abstract. In this study, an advanced measuring system with a tri-single-fiber-optical-probe has been developed to measure two-dimensional vapor/gas bubble velocity. The use of beam splitting devices instead of beam splitting lens simplifies the optical system, so the system becomes more compact and economic, and more easy to adjust. Corresponding to using triple-optical probe for measuring two-dimensional bubble velocity, a data processing method has been developed, including processing of bubble signals, cancelling of unrelated signals, determining of bubble velocity with cross correlation technique and so on. Using the developed two-dimensional bubble velocity measuring method, the rising velocity of air bubbles in gravitational field was measured. The measured bubble velocities were compared with the empirical correlation available. Deviation was in the range of $\pm 30\%$. The bubble diameter obtained by data processing is in good accordance with that observed with a synchroscope and a camera. This shows that the method developed here is reliable.

1. INTRODUCTION

Vapor/gas-liquid two-phase flows exist widely in the equipment of a lot of engineering area. To understand the two-phase flow behavior in the equipment is of great importance for its perfect design and safety analysis. The two-phase flow structures in some facilities such as in the rod bundles of nuclear reactors and in the tube bundles of steam generators are multi-dimensional and therefore are very complex. It is difficult to investigate the two-phase flow structures in the rod or tube bundles by experimental observation and measurements. With the development of computer technology, to use computational fluid dynamics (CFD) method to predict the two-phase flow characteristics in these facilities is considered. In order to verify the calculated results, it is necessary to obtain some information about two-phase flow in these devices such as the distribution of vapor bubble velocity, the vapor bubble size et al. Up till now, some advantage measurement methods, for example, particle image velocimetry (PIV) and particle tracking velocimetry (PTV) methods have been developed to measure directly the vapor bubble velocity fields and the distribution of vapor bubble size in multi-dimensional two-phase flows (Qu et al., 2004; Seol et al., 2007; Kawaguchi et al., 2005). However, these measuring devices are very complicated and expensive. Besides they are only suitable for the visual test facilities. Consequently the measuring systems consisting of many kinds of multi-sensor probes are rather simple and they can also be used to measure the parameters including the bubble velocities and the bubble size values of two-phase flows. The main problem is that a lot of probes available were only suitable for the measurement of local parameters of one-dimensional two-phase flows (Euh et al., 2005; El-Kamash et al., 2005; Ide et al., 2007; Chaumat et al., 2007). If ones
try to use the multi-sensor probe to measure the behaviors such as the bubble velocities of multi-
dimensional two-phase flow, they have to develop the technique of data processing of the signals from
all sensors responding to the same bubble. Some researchers have used multi-sensor probes to measure
the local time-averaged interfacial area concentration of the bubbles in multi-dimensional two-phase
flow (Shen et al., 2005). Few measurements of multi-dimensional bubble velocity by using probes
have been reported in the literature.

In this study, an advanced measuring system with a tri-single-fiber-optical-probe has been
developed to measure two-dimensional vapor/gas bubble velocity. During the data processing, the
technique of the rejection of non-correlation vapor/gas bubble signals has been developed. The
measuring system has been used to measure the two-dimensional velocities of air bubbles with free
upward flow in the stagnant water to verify the accuracy of the present measurement method.

2. MEASURING SYSTEM

An optical probe can distinguish liquid and vapor/gas phase by their different refractive index.
Generally speaking, void fraction can be measured by a single optical probe, one-dimensional bubble
velocity can be measured by a bi-optical probe. As for two-dimensional bubble velocity, it can be
measured only by optical probes with at least three single-fiber sensors.

The optical probe developed by the authors consists of three sensors. Each sensor is a single optical
fiber in itself 0.1 mm in diameter, with the sensing tip molten into a sharp cone and is sleeved with a
stainless steel tube 0.8 mm in diameter. The three sleeved fibers are assembled into one stainless tube
3 mm in diameter. The three sensing tips are arranged as a triangle in a plane parallel to the axis of the
sleeve. The construction of the optical probe and the arrangement of the three sensors are shown in
Fig. 1. The measuring system of the optical probe is schematically shown in Fig. 2.

In optical design instead of splitting lens which need accurate adjustment the beam splitting device
is used. So this measuring system is simple and has the advantage of easy adjustment. According to
the intensity required a He-Ne laser is used as the common light source for all three single-fiber
sensors. Two types of splitters are used in the system: one-in three-out type and Y-type. Besides the
tri-optical probe, the measuring system includes also photomultipliers, A/D converter and computer.

![Optical fiber arrangement](image)

Fig. 1 The construction of the tri-fiber-optical probe and the arrangement of its sensors

3. DATA PROCESSING

The data processing is rather simple for one-dimensional bubble velocity measurement. Bubble
velocity \( u \) can be obtained from the equation

\[
    u = \frac{L}{\tau_m}
\]

where \( L \) is the distance between two sensors and \( \tau_m \) the “flying time” of the bubble. But the two-or
three-dimensional velocity can not be obtained from eq.(1). As mentioned above, up to
now not so many papers related to measurement of two- or three-dimensional bubble velocity by using optical probe have been published, mainly because of the difficulties to develop an effective method for data processing. Firstly, it must be ensured that signals from different sensors are correlative with each other when measuring the bubble velocity, that is, signals from all sensors respond to the same bubble. All signals responding to bubbles which have not passed all the three sensors (unrelated signals) should be cancelled. Otherwise the measurement error will be great, that makes the results unreliable. In this sense, how to determine and cancel the unrelated signals becomes the key point of an effective measuring. Secondly, for measuring the two- or three-dimensional bubble velocity, it is necessary not only to determine the magnitude of the velocity, but also the movement direction of the bubble. The velocity direction is closely related to contact position of the bubble with the sensors and the flying time between the sensors. So another key point of realizing an effective measuring is to compose an algorithm with which the magnitude and direction of the velocity can be both determined. Having these two key points in mind, a data processing method for measuring two-dimensional bubble velocity has been developed. This method consists in following:

(1) Threshold for defining vapor/gas and liquid

The light signal reflected from the sensor is converted to electric signal and amplified. By means of A/D acquisition a set of varying with time digitized signals (voltages) can be collected in the computer. The ideal signals should be rectangular in shape. But in fact due to the surface tension there is some time delay when the sensor penetrates into the bubble and when the bubble leaves the sensor. So the signals obtained are not rectangular. The single threshold method is used to define whether the signal corresponds to vapor/gas phase or liquid phase. When the magnitude of the signal is larger than the threshold value, the sensor is located in vapor/gas phase, otherwise the sensor is in the liquid phase. And by this all the signals are transformed to rectangular shape. Based on the characteristics of the experimental system, in the present study the threshold value \( V \) for the signals (voltages) is chosen as:

\[
V = 0.3 \times (\text{max. signal value} - \text{min. signal value}) \quad (2)
\]

(2) Cancelling of unrelated bubbles

In vapor/gas -liquid two-phase flow due to the ambiguity of bubble movement and the difference in bubble size there may be some cases when a bubble passes the probe (refer to Fig. 3).

(a) The bubble passes one sensor only;
(b) The bubble passes two sensors;
(c) The bubble passes three sensors, but some sensor just touches the edge of the bubble;  
(d) The bubble passes all three sensors.

According to the correlation principle only case (d) is useful for the measurement. Bubbles passing
one or two sensors are not only useless, but also cause errors in calculation. Case (c) also causes
errors because signals from the sensor which only touches the edge of the bubble are too weak. So
before doing the correlation analysis cases (a), (b) and (c) must be defined and cancelled. Only the
signals of case (d) should be maintained. The method of cancelling unrelated bubble signals is as
follows. First, estimate the approximate range of bubble velocity \( (u_{\text{min}} \text{ and } u_{\text{max}}) \). Then estimate the
corresponding maximum and minimum flying time of bubble between sensors.

\[
t_{\text{min}} = \frac{L}{u_{\text{max}}} \quad (3)
\]

\[
t_{\text{max}} = \frac{L}{u_{\text{min}}} \quad (4)
\]

Signal detected by one sensor is used as comparison base. If in the maximum and minimum flying
time no signal is detected by the other two sensors, the case belongs to (a). If signal is detected by one
of the other two sensors in the time period the case belongs to (b). If in this time period the other two
sensors also give signals the case belongs to (c) or (d). Thus, cases (a) and (b) can be defined and
cancelled easily. By comparing the impulse width, case (c) can be defined and then cancelled. The
criteria are:

\[
\varepsilon_1 < 2t_1 / (t_1 + t_2) < \varepsilon_2 \quad (5a)
\]

\[
\varepsilon_1 < 2t_1 / (t_1 + t_3) < \varepsilon_2 \quad (5b)
\]

where \( \varepsilon_1, \varepsilon_2 \) are constant and are given (\( \varepsilon_1 < 1, \varepsilon_2 > 1 \)) (Zheng, 1996), \( t_1, t_2 \) and \( t_3 \) are the impulse width of
bubble signals from the three sensors accordingly, i.e., the contact time of bubble with the sensor.
When the signals meet the inequality (5), it is recognized as case (d). Otherwise the bubble signals
belong to case (c) and should be cancelled.

(3) Determination of “flying time” by cross correlation techniques

After cancelling of the unrelated signals the cross correlation functions \( R_{12}(\tau), R_{13}(\tau) \) and \( R_{23}(\tau) \)
for each two sensors of the three sensors are calculated from the equation:

\[
R_{xy}(\tau) = \frac{1}{T} \int_0^T x(t) \times y(t + \tau) dt \quad (6)
\]

and the “flying time” \( \tau_{12}, \tau_{13} \) and \( \tau_{23} \) corresponding to the maximum value of the cross
Correlation functions \( R_{12}(\tau), R_{13}(\tau) \) and \( R_{23}(\tau) \) are determined.

(4) Solving for the magnitude and direction of bubble velocity

Assume that the bubble is spherical, that the deformation of its shape when it touches and leaves the
probe can be neglected or the bubble deformation when it touches and leaves the probe is the same
and that the bubble velocity remains unchanged when it is in touch with the probe. As shown in Fig.4,
the bubble passing through three sensors should have a velocity as \( L_{2c}/\tau_{12} \) or \( L_{3b}/\tau_{13} \) with a direction
angle of \( \theta \). In order to calculate the velocity the distance \( L_{2c} \text{ or } L_{3b} \) is required. The distance in turn is
dependent on the bubble velocity, the arrangement of sensors in the plane and the bubble size. So the
bubble velocity can be determined only by iteration. Assume the bubble velocity \( u_0 \), determine the
bubble size according to “flying time”, and then determine \( L_{2c} \text{ or } L_{3b} \) in relationship with the
geometry of probe and bubble. Thus, a new velocity can be obtained. Use the newly obtained velocity
instead of \( u_0 \) and repeat the process until convergence is reached. The iteration process is as follows
(refer to Fig. 4):
(4.1) Calculate the chords of the bubble

\[ L_{li} = t_1 \times u_0, \quad L_{cj} = t_2 \times u_0, \quad L_{bh} = t_3 \times u_0 \]  

(7)

where \( t_1, t_2, t_3 \) are the impulse width (the width of the rectangular wave) of bubble signal from sensor 1#, 2# and 3# respectively.

(4.2) Calculate the transport distance

\[ L_{2c} = \tau_{12} \times u_0, \quad L_{3b} = \tau_{13} \times u_0 \]  

(8)

(4.3) Estimate the direction of bubble movement

As shown in Fig. 4a

\[ L_{3d} = (0.5 \times L_{bh} + L_{3b}) - (0.5 \times L_{cj} + L_{2c}) \]  

(9a)

As shown in Fig. 4b

\[ L_{2d} = (0.5 \times L_{cj} + L_{2c}) - (0.5 \times L_{bh} + L_{3b}) \]  

(9b)

If \( L_{3d} \geq 0 \), the bubble moves towards left to the sensor 3# as shown in Fig. 4a, and

\[ \theta = \arcsin \left( \frac{L_{3d}}{L_{23}} \right) \]  

(10a)

If \( L_{3d} < 0 \), the bubble moves towards right to the sensor 2# as shown in Fig. 4b, and

\[ \theta = \arcsin \left( \frac{L_{2d}}{L_{23}} \right) \]  

(10b)

where \( L_{23} \) is determined by the geometry of the probe.
(4. 4) Calculate the new value of the velocity 
Refer to Fig. 4a as an example:

\[ L_{ag} = L_{1g} \times \tan \theta \]  
(11a)  
\[ L_{2a} = L_{ag} + L_{2g} \]  
(11b)  
\[ L_{ae} = L_{2a} \times \sin \theta \]  
(11c)  
\[ L_{da} = L_{ag} \div \cos \theta \]  
(11d)  
\[ L_{de} = L_{da} - L_{ae} \]  
(11e)  
\[ L_{ck} = 0.5 \times (L_{ll} - L_{lj}) \]  
(11f)  
\[ L_{2c} = L_{de} + L_{ck} \]  
(11g)  

So the bubble velocity is 
\[ u = L_{2c} \div \tau_{12} \]  
(11h)  

where \(L_{1g}, L_{2g}\) are determined by the geometry of the probe.

According to Fig. 4b, \(L_{3b}\) and the respective bubble velocity \(u\) can be determined in the same way.

(4. 5) Convergence discrimination 
If \(|u - u_0| \geq \varepsilon\), \(\varepsilon\) is the convergence factor, let \(u_0 = u\), return to step (4.1) and continue iteration.

If \(|u - u_0| < \varepsilon\), end the iteration process. The bubble velocity is \(u\), the included angle between the direction of movement and the vertical is \(\theta\).

(4. 6) Calculation of the bubble diameter 
According to Fig. 4

\[ L_{mn} = L_{23} \times \cos \theta \]  
(12a)  
\[ L_{mn} = L_{om} + L_{on} \]  
(12b)
The bubble diameter $D$ can be obtained by solving the equations (12a) and (12c) simultaneously.

4. MEASUREMENT OF THE RISING BUBBLE VELOCITY

The test facility used for measuring the velocity of rising bubbles in stagnant water is shown in Fig. 5. Air is injected into distilled water through a syringe needle at the bottom of a plexiglass tube. In the upper part of the plexiglass tube the air bubbles rise freely. The triple-optical probe is located in the upper part and the plane of its three sensors is parallel to the axis of the tube. The visual observation shows that the bubble does not move vertically upwards, but spirals. That is, the upward movement of the bubble is S-shaped.

![Fig. 5 The rising bubble velocity measuring facility](image)

The output signals of the three sensors are collected simultaneously. For each velocity measurement $3 \times 15000$ data points are sampled. The time interval of sampling is 0.3ms. Bubble velocity is obtained by the data processing technique mentioned above, where $\epsilon_1=0.4, \epsilon_2=1.6, u_{\text{min}}=0.044 \text{ m/s}, u_{\text{max}}=0.273 \text{ m/s}$. The typical results obtained are listed in Table 1. In Table 1 the void fraction measured by each sensor is calculated as follows:

$$\alpha = \frac{\text{Data points of signal (voltage) with the value greater than the threshold value}}{\text{Total data points of signal (voltage)}}$$

It can be seen from Table 1 that the bubbles do not move vertically upwards. This is in accordance with the observation.

During the experiment the bubble diameter is observed with a synchro-scope and a camera. The bubble diameter obtained by data processing is in accordance with the investigated. This shows also that the method developed here is reliable for measuring two-dimensional bubble velocity. There were many experiments carried out for measuring the rising velocity of a bubble in gravitational field. The bubble rising velocity can be described by the following expression (Wallis, 1969):

$$u_b = 1.18 \left[ \sigma g (\rho_f - \rho_g) / \rho_f^{0.25} \right]^{0.25}$$

(14)

where $\sigma$ is surface tension, $g$ gravitational acceleration, $\rho_f$ and $\rho_g$ are liquid and vapor/gas density respectively. For the experiment condition presented in this paper the calculated with equation (14) bubble velocity is $u_b=0.108 \text{ m/s}$. The comparison of measured and calculated vertical component of the velocity is shown in Fig. 6. The deviation is within $\pm 30\%$. It should be noted that even in a stable two-phase flow field the bubble velocity varies with time and eq.(14) gives the mean rising velocity of the bubble. The comparison shows that the velocity measured in the present system can be described by eq.(14).
If data are processed without canceling of the unrelated signals, as shown in Table 1, 4 sets of signals will not converge in the iteration process and the velocity and its direction can not be obtained. From the other 5 sets of signals the magnitude and direction of the velocity can be obtained, but the velocity value is more discrepant, from 0.04 to 0.198 m/s. This shows the strong influence of unrelated signals. This also shows that the cancelling method presented here is successful.

| No | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    |
|----|------|------|------|------|------|------|------|------|------|
|    |      |      |      |      |      |      |      |      |      |
| Void fraction, sensor 1# | 0.245 | 0.233 | 0.295 | 0.244 | 0.234 | 0.286 | 0.290 | 0.169 | 0.264 |
| Void fraction, sensor 2# | 0.262 | 0.214 | 0.263 | 0.253 | 0.226 | 0.267 | 0.299 | 0.199 | 0.221 |
| Void fraction, sensor 3# | 0.178 | 0.327 | 0.356 | 0.189 | 0.256 | 0.292 | 0.297 | 0.276 | 0.326 |
| Mean void fraction | 0.288 | 0.258 | 0.305 | 0.229 | 0.239 | 0.282 | 0.295 | 0.215 | 0.270 |

| Velocity magnitude, m/s | — | — | 0.049 | — | 0.093 | 0.123 | 0.178 | — | 0.198 |
| Direction angle, degrees | — | — | 10.4 (a) | — | 18.4 (b) | 5.7 (a) | 0.1 (a) | — | 3.9 (b) |

| Velocity magnitude, m/s | 0.148 | 0.085 | 0.117 | 0.137 | 0.138 | 0.119 | 0.122 | 0.091 | 0.095 |
| Direction angle, degrees | 20.8 (b) | 3.7 (a) | 13.7 (a) | 6.6 (b) | 15.5 (b) | 17.8 (a) | 3.7 (b) | 21.8 (b) | 0.0 |
| Bubble diameter, mm | 4.51 | 5.12 | 4.39 | 6.86 | 6.08 | 6.39 | 5.57 | 6.14 | 7.01 |

5. CONCLUSIONS
(1) The optical probe with three single-fiber sensors developed here can effectively get signals from the vapor/gas and liquid phases. The use of beam splitting devices instead of beam splitting lenses simplifies the optical system, so the system becomes more compact and economic, and more easy to adjust. The sensor manufacturing method, melting the optical fiber tip to form a sharp corn is convenient. The sensor has little influence on the flow and has high dynamic responsibility. The system used here does not require large signal amplitude and is simple to handle.

(2) Corresponding to using triple-optical probe for measuring two-dimensional bubble velocity a data processing method has been developed, including processing of bubble signals, cancelling of unrelated signals, determining of bubble velocity with cross correlation technique and so on.

(3) Using the developed two-dimensional velocity measuring method, the rising velocity of air bubbles in gravitational field was measured. The results of bubble velocity were compared with the empirical correlation available. Deviation was in the range of ±30%. The bubble diameter obtained by data
processing is in good accordance with that observed with a synchro-scope and a camera. This shows
that the method developed here is reliable.

Fig. 6  Comparison of the measured and calculated velocity

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NOMENCLATURE

\[ L \] distance \ [m] \\
\[ t \] impulse width of bubble signal (time) or flying time of bubble \ [s] \\
\[ u \] velocity \ [m/s] \\

Greek Letters

\[ \alpha \] void fraction \\
\[ \theta \] direction angle of bubble movement \ [degree] \\
\[ \tau \] flying time of bubble \ [s] \\

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