A three-dimensional photographic method for measurement of phase distribution in dilute bubble flow

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Abstract A three-dimensional photographic method has been developed to measure phase distributions in bubbly flow in a pipe. In this method a mirror was used to reflect a side view of the flow into the front-view direction, and then flow images in both views were taken simultaneously by one camera. After three-dimensional position and size of each bubble in the flow field were determined by matching the two bubble images in the side and front views, the phase distributions were obtained for the bubbly flow.

Keywords Three-dimensional photography, Phase distribution, Bubbly flow

1 Introduction
The photographic method is considered to be an absolute and standard method for two-phase flow measurements and is usually used to calibrate other methods such as probes, in particular for low-void-fraction flows (Revankar and Ishii 1992). However, direct application of conventional photography is only capable of measuring bulk parameters rather than their distributions in the flow field. To study phase distributions in two-phase flow, if intrusive methods like probes are not acceptable (Alajbegovic et al. 1994) and detailed information about the interfacial structure is desired (Revankar and Ishii 1993), stereophotography may be a good alternative. Murai et al. (1997) measured bubble and liquid velocity distributions in bubbly flow. Hassan et al. (1998) obtained the detailed velocity, turbulence, and interfacial structure distributions in a single-bubble rising flow.

This paper presents a three-dimensional photographic system consisting of a camera plus a mirror instead of two cameras, which makes the system much simpler. As a result, the direct and simple geometric relationships relating the mirror, the flow, and the camera allow accurate determination of the bubble positions.

2 Measurement method

2.1 Arrangement of 3-D photography system
Determination of the three-dimensional position of a bubble in a flow field requires two different views of the flow field. Two pairs of the two-dimensional coordinates of the projection of the bubble in each view can be used to determine the three-dimensional coordinates of the bubble in space (Adrian 1991). A good arrangement for the two views is one in which the two views are perpendicular to each other (Yamamoto et al. 1998; Hassan et al. 1998), see Fig. 1. Consider bubbly flow in a pipe in the z-direction, the front view is from the x-direction, and the side view is from the y-direction in the coordinate system, as shown in Fig. 1d. To eliminate the optical deformation due to the lens effect of the liquid-filled circular pipe, the pipe is enclosed by a square transparent box, and the box is filled with the same liquid as the working fluid.

A camera is arranged to take the front view of the bubbly flow. A mirror is used to reflect the side view from the y-direction into the x-direction. Therefore the side-view image will be taken simultaneously with the front view by the camera (Fig. 1c). Then the x-z-plane image of the flow will be in the side view (Fig. 1b), and the y-z-plane image will be in the front view (Fig. 1a).

The camera was aligned so that its line of sight was perpendicular to the flow direction. The horizontal plane through the line of sight was used as the base plane. The Cartesian coordinate system origin is set at the pipe center in the base plane, as shown in Fig. 2. Horizontal positioning lines were marked on the envelope box of the test section at the base plane and at the z-coordinates of H and -H.

2.2 Determination of 3-D bubble positions
The three-dimensional positions of every bubble in the flow field were determined from the x-z- and y-z-plane images. The key is to match the x-z-plane image of a bubble to its corresponding y-z-plane image. It is not difficult to see that the two images have the same coordinate z. Therefore the counterpart in the x-z-plane image of a bubble in the y-z image of the flow is found using the common z-coordinate of the two bubble images.

Consider a bubble in the flow field, see Fig. 2. The real position of the bubble center is (x, y, z). So the coordinate z of the bubble center can be calculated from the front-view image by...
\[ y = \frac{L + \frac{w}{2} + x}{L + a + b} (Yo' + y') - \left( R + \frac{d}{2} \right) \]  

(6)

where \( R \) is the inner radius of the pipe. The values of \( L, a, b, d, \) \( Xo' \) and \( Yo' \) can be obtained from the images of the length scales marked on the measurement section.

\[ L = \frac{WH''}{(H'' - H')} \]  

(7)

\[ a = L \left( \frac{H''}{H'} - 1 \right) \]  

(8)

\[ b = LH'' \left( \frac{1}{H - \frac{1}{H'}} \right) \]  

(9)

\[ d \approx \frac{L + \frac{a}{2}}{L + a + b} d' \]  

(10)

\[ Xo' = \frac{L + a + b}{L + \frac{w}{2}} \left( R + \frac{d}{2} \right) \]  

(11)

\[ Yo' = \frac{L + a + b}{L + \frac{w}{2}} \left( R + \frac{d}{2} \right) \]  

(12)

where \( H', H'', \) and \( H''' \) are the heights of the marked contour lines in the side- and front-view images, see Fig. 2, and \( d' \) can be obtained from sharp images of the inside wall of the pipe. Values of \( z_F, z_S, h_F, \) and \( h_S \) can be calculated from (1)–(12).

Each pair of \( x \)- and \( y \)-coordinates of a bubble center in (5) and (6) should satisfy the condition that the pipe wall cannot be penetrated by the bubble. So, if we consider bubbles as ellipsoids

\[ x^2 + y^2 \leq (R - l_b/2)^2 \]  

(13)

where \( l_b \) is the major axis length of the bubble’s projection on \( x-y \)-plane. However, \( l_b \) cannot be known exactly. We can estimate \( l_b \) from its \( x \)-component, \( l_{bX} \), and its \( y \)-component, \( l_{bY} \). But before \( x \) and \( y \) are determined, \( l_{bX} \) and \( l_{bY} \) are still unknown. From Fig. 2 and (3)

\[ l_{bY} \geq \frac{L}{L + a + b} l_{bY} \]  

(14)