# Three-dimensional measurement of bubble volume based on dual perspective imaging*

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This paper presents a new three-dimensional (3D) volume measurement approach of bubble in gas-liquid two-phase flow. According to the dual perspective imaging principle, bubble feature images can be captured from two different view angles. The least square ellipse fitting algorithm is used to figure out the feature parameters from the captured images. Then the 3D volume of bubble can be quantitatively measured. Compaerd with the traditional volume estimation methods based on single perspective imaging, it can effectively reduce the loss of bubble feature information. In the experiment, the 3D volume reconstruction of bubbles from dual perspective images is conducted, and the variation of bubble volume in the bubble rising process is studied. The results show that the measurement accuracy based on the proposed 3D method is higher than those based on traditional methods. The volume of rising bubble is periodically changed, which indicates that bubble achieves periodic rotation and deformation in the rising process.

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Gas-liquid two-phase flow has been widely used in many fields, such as chemical, nuclear, petroleum and fluid mechanical engineering. With the rapid development of measurement technology, the feature parameters of bubble in gas-liquid two-phase flow have been studied further[1-3]. In the industrial process, the measurement of bubble parameters is of great importance, because they determine the performance of discrete phase and continuous phase in two-phase flow. For example, bubbles exist in the form of the dispersed phase in fluidized bed, and their volume and modality can affect the mass transfer area, as well as the reaction efficiency[4,5]. As the bubbles volume is known, the concentration and distribution characteristics of two phases can be calculated, and then the hybrid density and pressure gradient can be acquired.

At present, the measurement method based on high-speed photography for bubble feature parameters has become the hot spot due to its merits of non-contact measurement, instantaneity and full detection[6]. But most studies are concentrated on the single perspective imaging. Bröder et al[7] developed an online measurement system of bubble size, volume and velocity based on planar shadow imaging. Fan et al[8] investigated the influence of orifice spacing on the generated bubble shape and volume by means of visualized images. Altheimer et al[9] presented an image processing sequence to determine the bubble dimensions from overlapping bubble shadows by the least square ellipse fitting. The above methods calculate bubble volume through a single two-dimensional (2D) imaging plane to estimate the equivalent diameter of bubble body or the length of the third axis approximately, therefore, the limitation is obvious. It is easy to lose the projection information and decrease the measurement accuracy.

In the previous investigations, Xue et al[10,11] has established a dual perspective imaging system to reconstruct the three-dimensional (3D) motion trajectories and velocity vectors of bubbles, in which the bubbles are regarded as points and the bubble volume are not measured. Therefore, for the key parameters of bubble volume, a novel reconstruction method for the 3D volume of bubbles in gas-liquid two-phase flow based on the dual perspective imaging system is proposed in this paper.

The dual perspective imaging system consists of one high-speed camera and two sets of symmetrical reflectors. The camera is mirrored as two virtual ones to offer two different view angles for objects. Taking one bubble in flow field for example, it can be seen as an ellipsoid approximately in most cases. The projection relationship

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of an ellipsoid bubble in these two virtual imaging planes is shown in Fig.1. No matter how the bubble locates in the field of view (FOV), three axial data of the bubble can always be captured by the high-speed camera. Moreover, the two virtual imaging planes are vertically aligned, and the captured time of two projections is seriously synchronous. Therefore, the 3D structure of bubble can be reflected in the left and right imaging planes effectively.

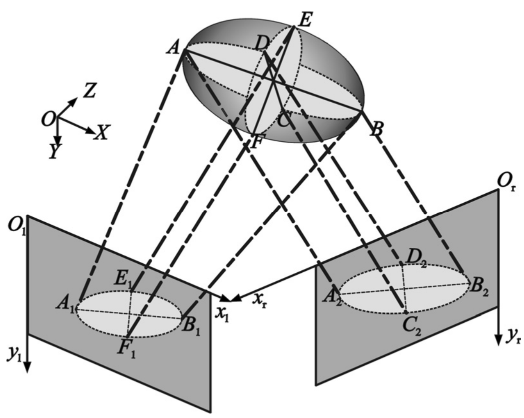



**Fig.1 Schematic diagram for the projection of an ellipsoid bubble in two virtual imaging planes**

The feature parameters from bubble projection, including the centroid position, the lengths of long axis and short axis and the angle between the long axis and the horizontal axis (the directional angle), can be calculated by the least square ellipse fitting algorithm. It is supposed that the centroid coordinate, the lengths of long axis and short axis and directional angle of bubble in the left projection plane are ($x_{0L}$, $y_{0L}$), $r_{1L}$, $r_{2L}$ and $\theta_L$, respectively. Similarly, these parameters in the right projection plane are defined as ($x_{0R}$, $y_{0R}$), $r_{1R}$, $r_{2R}$ and $\theta_R$, as shown in Fig.2.

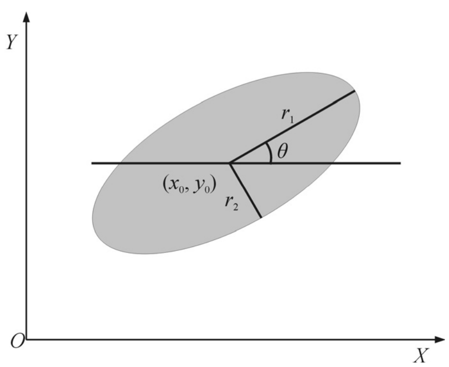



**Fig.2 Projection of bubble in imaging plane**

Then the boundary equation of bubble in the left or right projection plane can be expressed as

$$\frac{[(x-x_0)\cos\theta+(y-y_0)\sin\theta]^2}{r_1^2}+\frac{[-(x-x_0)\sin\theta+(y-y_0)\cos\theta]^2}{r_2^2}=1. \quad (1)$$

If the elliptic bubble boundary curve is given by

$$x^2+Axy+By^2+Cx+Dy+E=0, \quad (2)$$

where ($x$, $y$) is the coordinate of point on the ellipse, and $A$, $B$, $C$, $D$ and $E$ are known coefficients, then the axis length of bubble projection can be calculated as

$$r_1=\sqrt{\frac{2(ACD-BC^2-D^2+4BE-A^2E)}{(A^2-4B)(B-\sqrt{A^2+(1-B)^2}-1)}}, \quad (3)$$

$$r_2=\sqrt{\frac{2(ACD-BC^2-D^2+4BE-A^2E)}{(A^2-4B)(B+\sqrt{A^2+(1-B)^2}-1)}}. \quad (4)$$

The variables $A$, $B$, $C$, $D$ and $E$ can be figured out by the least square ellipse fitting. Firstly, an objective function is established as

$$F(A,B,C,D,E)=\sum_{i=1}^{N}(x_i^2+Ax_iy_i+By_i^2+Cx_i+Dy_i+E)^2, \quad (5)$$

where ($x_i$, $y_i$) denotes the image coordinate of the point on the bubble boundary. Then the objective function should be minimized to figure out $A$, $B$, $C$, $D$ and $E$. By these five parameters, the lengths of long axis and short axis can be calculated as Eqs.(3) and (4).

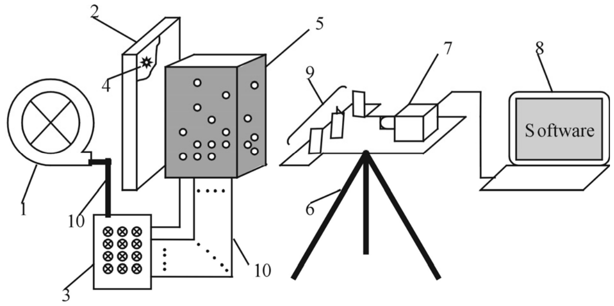
The bubble volume can be reconstructed from these two virtual imaging planes. Suppose that the angle between the two imaging planes is $\alpha$. Therefore, the 3D axis lengths $a$, $b$ and $c$ at three perpendicular directions of bubble in Fig.1 can be acquired from the dual perspective images, which can be expressed as

$$\begin{cases} a=[r_{1L}+r_{1R}/\cos(\alpha-90°)]/2 \\ b=r_{2L} \\ c=r_{2R}/\cos(\alpha-90°) \end{cases}. \quad (6)$$

Finally, the bubble volume can be calculated by

$$V=4\pi abc/3. \quad (7)$$

The experimental setup is shown in Fig.3, which mainly includes the appliance for producing bubble, the dual perspective imaging system, the lighting system and the processing software platform. The liquid phase in the experiment is tap water, and the gas phase is compressed air injected into the tank through the air compressor, air regulators, simple connectors and the air distributor in turn. The dual perspective imaging platform is placed in front of the water tank, and the light-emitting diode (LED) array illuminates the bubbles from the back of the tank. Some orifices with diameters of 1 mm, 2 mm, 3 mm and 4 mm are arranged on the bottom of water tank, and the air flow and pressure are measured by Alicat flow meter. The original images (960×720) are captured at 100 frames per second.




1: air compressor, 2: background light source (LED array), 3: air regulators, 4: LED, 5: water tank, 6: tripod, 7: high-speed camera, 8: computor, 9: dual perspective imaging platform, 10: air pipe

**Fig.3 Schematic diagram of experimental setup**

The dual perspective imaging system is composed of one high-speed camera (SpeedCAM MiniVis E2) with 35 mm Nikkor lens and two front surface reflector groups. According to the calibration of measurement system[12], its structure parameters can be achieved accurately. In the system, the angle between the left and right virtual imaging plane is 110.09°, i.e., the parameter $\alpha$ which is used for calculating the bubble axis lengths in Eq.(6) equals to 110.09°.

The bubble volume is measured based on the proposed approach. To verify the measurement accuracy of the volume parameters, the obtained parameter values should be compared with the real values. In the experiment, an air flow meter is used to measure the gas volume, which can be taken as the sum of bubbles' volume. Under a certain air flow $v$, the high-speed camera takes $N$ frames of bubbles. In this period of time, the total volume of the air injected into the water is $vN/f$, where $f$ is the frame rate of camera. The volume of injected air is calculated by the 3D measurement method in this paper. The measured volume values through the 2D bubble images based on the traditional left or right 2D images of the bubble projection are compared. In the experiment, the air flow $v$ is changed four times. For each air flow value, the measurement is conducted five times to reduce the random error.

The measurement results of bubble volume by different methods are shown in Fig.4. A bubble is regarded as spherical modal in the traditional measurement method, so the equivalent radius of the bubble is easy to figure out. From Fig.4, it can be seen that the measured bubble volume based on single perspective imaging methods cannot reflect the real value exactly, while in this paper can perform with high accuracy, and bubble volume obtained by the 3D measurement method is closer to the real value than those obtained by 2D measurement methods. As shown in Fig.5, the measurement error of bubble volume with the proposed 3D measurement method is lower than ±15%.

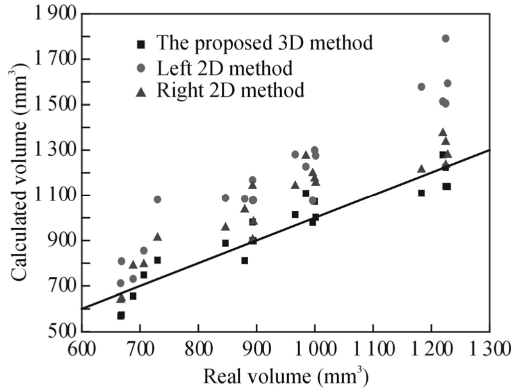



**Fig.4 The measurement results of bubble volume obtained by various methods**

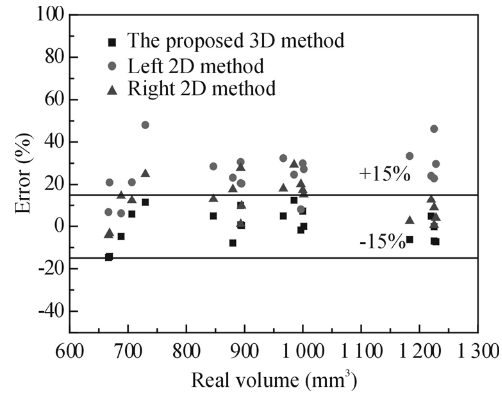



**Fig.5 The measurement errors of bubble volume by various methods**

The volume variation of bubble rising in the water is measured and shown in Fig.6. Obviously, crest and trough appear periodically, which means periodic bubble deformation in the rising process. It can be deduced that the forces on bubble surface are not balanced when the bubble rises, which leads to the bubble rotation and transformation due to extrusion.

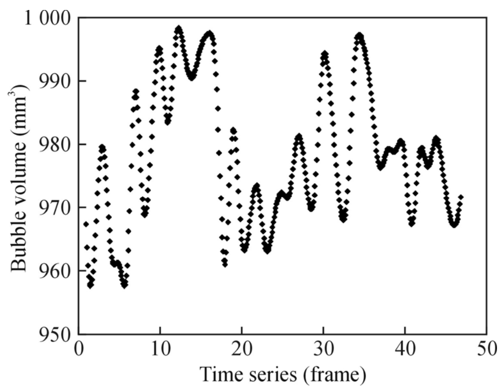



**Fig.6 The volume variation of rising bubble**

In this paper, a 3D volume measurement method of bubble in gas-liquid two-phase flow is proposed based on dual perspective imaging and the least squares ellipse fitting algorithm. It can effectively avoid the loss of feature information of bubble. We measure the volume of bubble in the experiment and study the volume variation in the bubble rising process. The result indicates that the measurement accuracy of the proposed method with the error lower than ±15% is much higher than those of the traditional single perspective imaging methods. The variation of bubble volume is approximately periodic when bubble is rising, and the peaks and troughs appear alternately, which shows the bubble rotation and deformation during the rising process.

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