Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 22, 2009

Simultaneous Measurements of Size and Velocity of Bubbles in an Opaque Tube Using X-ray PTV Technique

Seok Kim[a*], Sang Joon Lee[b], Chul Hwa Song[a]
[a]*Korea Atomic Energy Research Institute, Daeduk-daero 1045, Yuseong-gu Daejeon, 305-353, Republic of Korea*
[b]*Department of Mechanical Engineering, POSTECH, San31, Hyoja-dong Pohang, 790-784, Republic of Korea*
[*]*Corresponding author: seokim@kaeri.re.kr*

1. Introduction

An X-ray PTV (particle tracking velocimetry) technique was developed to measure size and velocity of bubbles simultaneously without any optical aberrations. This advanced experimental technique is based on the combination of the in-line X-ray holography and 2-frame PTV method. The X-ray PTV is simple to adopt and its configuration is similar to conventional optical imaging techniques. The bubbles made by air explosion were used as tracer particles. The size and velocity information of bubbles (10~60μm) moving upward in an opaque tube (ϕ=2.7mm) were measured simultaneously using the X-ray PTV technique. Due to different refractive indices of water and air, phase contrast X-ray images show clearly the exact shape of overlapped bubbles. For several working fluids of DI water and NaCl electrolyte solutions, the measured up-rising terminal velocity of bubbles is proportional to the square of bubble diameter. This advanced technique can be applied to get useful information of two-phase fluid flows for which conventional optical methods have difficulties to analyze.

2. Methods and Results

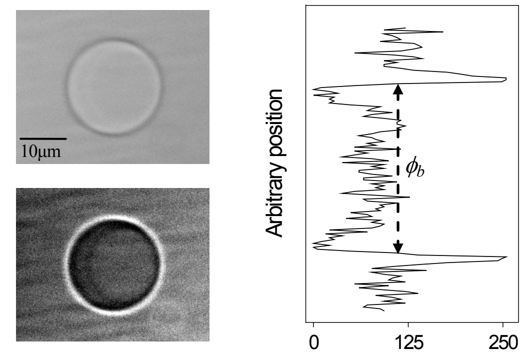
2.1 Measuring Bubble Size and Velocity

Recent advances in digital image processing techniques have made it possible to extract quantitative information from visualized flow images. Particle image velocimetry (PIV) and particle tracking velocimetry (PTV), which use digital image processing of tracer particles seeded in a flow, have been accepted as a reliable velocity field measurement technique. However, conventional flow visualization techniques including PIV/PTV are ill suited for measuring flow information of non-transparent fluids or fluids inside opaque conduits. To resolve these limitations, we need to use a transmission-type light source such as an X-ray source instead of visible light sources. The third generation synchrotron radiation source of PLS (Pohang Light Source) was used as a light source in this study. The coherent X-ray beam provides clear phase contrast images, while transmitting a certain volume of object. The measurement of entire velocity field of a two-phase flow enclosed in a small opaque conduit has not been reported yet.

For measuring the spatial distribution of size and velocity of bubbles moving in an opaque tube, we enhanced the X-ray micro-imaging technique and optimized the experimental conditions such as the object-detector distance (Lee et al. 2003). The edge enhancement method based on diffraction mechanism of coherent X-ray beam makes it possible to visualize the invisible internal structure of opaque objects in detail. The diffraction-based edge enhancement method is based on the phase contrast imaging instead of the conventional X-ray absorption method. It makes the boundary of bubbles visualize clearly.

2.2 Experimental Method

An X-ray beam of sufficient coherence can induce the Fresnel edge diffraction pattern in radiological images. In general, the fringe pattern by edge diffraction becomes clearer as the object-detector distance is increased. The performance of diffraction-based edge detection depends on several factors such as beam monochromaticity, source size and lateral resolution of the detector. In this study, the X-ray imaging technique with the Fresnel diffraction pattern method was employed to measure the size of bubbles. For the case of conventional imaging with a visible ray, light scattering and re-fraction occur on boundaries (or interfaces) of gas bubbles. They make it difficult to determine the exact size of bubbles. However, using the synchrotron X-ray micro-imaging technique, we can get edge-enhanced diffraction (Fresnel diffraction) pattern at boundary (or interface) of gas bubbles. Due to different refractive indices between gas and liquid, the X-ray image shows clearly the exact shape of a bubble tested. The edge enhancement method requires a superior detector with a high spatial resolution. On the other hand, as the spatial resolution of the detector increases, the diffraction fringes are converted to the refraction fringes for a given distance ro between the sample and the recording detector (Hwu et al. 1999). In real experimental setup, a detector with a fixed spatial resolution has suitable distance r_o for obtaining clear diffraction fringes. The Fresnel diffraction pattern is affected by spatial resolution of a recording device (Δz) and recording distance (r_o) from the object to the recording detector. The raw image is inverted as shown in Fig. 1(a) to enhance the image. Figure 1(b) represents a gray level intensity profile extracted along a vertical



(a) Raw and inverted images (b) Gray level intensity

Fig. 1. Typical diffraction pattern of a bubble.

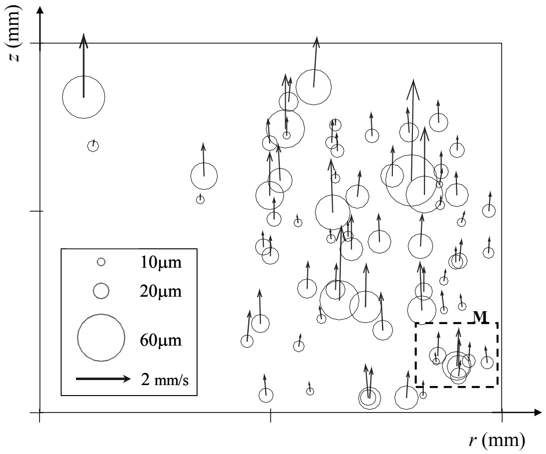
center line of the captured micro-bubble. It shows a typical pattern of Fresnel diffraction. The size ϕ_b of a micro-bubble is determined from its Fresnel diffraction pattern.

Instantaneous velocity fields of bubbles were measured by applying a 2-frame PTV (particle tracking velocimetry) method (Baek et al. 1996) to X-ray images of bubbles. The 2-frame PTV method tracks displacement of each matched particle pair in consecutive image frames. From displacement information of centroids of bubbles during a short time interval, the directionally resolved velocity vectors of bubbles were obtained accurately. X-ray images were recorded consecutively with a digital CCD camera for subsequent data processing. The size and velocity vector of each micro-bubble captured from the near-field radiation pattern was superimposed to give whole information together.

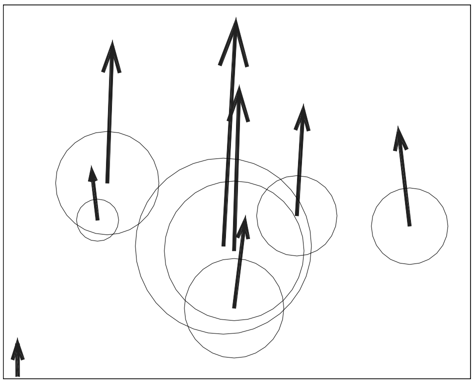
2.2 Experimental Results

Figure 2(a) shows instantaneous distribution of the size and velocity of bubbles rising in 0.10 M NaCl solution. The size of bubbles measured is ranged from 10μm to 60μm and the corresponding Reynolds number is less than Re=0.5. The field of view is 858μm ×686μm in physical size. The consecutive images of bubbles show a spiral motion with a large pitch. Due to buoyancy, all bubbles rise in the tube and have wide distribution in size and velocity. Figure 2(b) is the enlarged view of the region marked in the right bottom corner. For the case of conventional visible ray methods, the overlapped bubbles are usually discarded during the post-processing routine. However, the X-ray micro-imaging technique can distinguish clearly individual bubbles from the overlapped images as shown in Fig. 2(b).

The X-ray PTV technique was applied to measure simultaneously the size and velocity of bubbles moving upward in an opaque tube. This advanced technique can be used to get useful information of two-phase fluid flows for which conventional methods have difficulties to apply.



(a) Instantaneous distribution



(b) Enlarged view of the region marked as M

Fig. 2. Instantaneous distribution of the size and velocity of bubbles at 0.10 M NaCl solution.

3. Conclusions

The advanced X-ray PTV technique was used to measure quantitative information such as size and velocity vector distributions of bubbles moving inside an opaque material. We established the diffraction-based edge enhancement method for X-ray micro-imaging and optimized the object-detector distance. Compared with conventional measurement techniques, this X-ray imaging technique has high spatial resolution and can distinguish clearly overlapped bubbles.

REFERENCES

[1] S. J. Lee, G. B. Kim, X-ray Particle Image Velocimetry for Measuring Quantitative Flow Information inside Opaque Objects, Journal of Applied Physics, Vol.94, p.3620, 2003.

[2] Y. Hwu, H. H. Hsieh, M. J. Lu, W. L. Tsai, H. M. Lin, W. C. Goh, B. Lai, J. H. Je, C. K. Kim, D. Y. Noh, H. S. Youn, G. Tromba, and G. Margaritondo, Coherence-enhanced Synchrotron Radiology: Refraction versus Diffraction Mechanisms, Journal of Applied Physics, Vol.86, p.4613, 1999.

[3] S. J. Baek, S. J. Lee, A New Two-frame Particle Tracking Algorithm using Match Probability, Experiment in Fluids, Vol.22, p.23, 1996.