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Letter

Visualisation of air–water bubbly column flow using array Ultrasonic Velocity Profiler

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HIGHLIGHTS

- An experimental study of bubbly two-phase column flow performed using two ultrasonic array sensors, which can measure the instantaneous velocity of gas bubbles on multiple measurement lines.
- The sound pressure distribution of array sensors evaluated with a needle hydrophone technique.
- To assess the accuracy of the measurement system with array sensors, a simultaneous measurement performed with Particle Image Velocimetry (PIV) technique.

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ABSTRACT

In the present work, an experimental study of bubbly two-phase flow in a rectangular bubble column was performed using two ultrasonic array sensors, which can measure the instantaneous velocity of gas bubbles on multiple measurement lines. After the sound pressure distribution of sensors had been evaluated with a needle hydrophone technique, the array sensors were applied to two-phase bubble column. To assess the accuracy of the measurement system with array sensors for one and two-dimensional velocity, a simultaneous measurement was performed with an optical measurement technique called particle image velocimetry (PIV). Experimental results showed that accuracy of the measurement system with array sensors is under 10% for one-dimensional velocity profile measurement compared with PIV technique. The accuracy of the system was estimated to be under 20% along the mean flow direction in the case of two-dimensional vector mapping.

Two-phase flows can be encountered in a wide variety of industrial applications including nuclear reactors, boilers, chemical reactors, etc. It has been under a continuous investigation over the past several decades due to its complexity such as its turbulent phenomena, bubbles motion and so on. Bubble column is a commonly used way to investigate two-phase flow due to its relatively simple construction, ease of operation, and good mixing characteristics [1]. In the study of two-phase flows, the knowledge of velocity and volume fraction is very important for better understanding of transport phenomena in two-phase flow systems. Thus, many measurement techniques have been developed for volume fraction such as electrical resistivity probe (ERP), wire mesh sensor (WMS) and velocity such as particle image velocimetry (PIV) and laser Doppler velocimetry (LDV) etc. Point measurement techniques, such as ERP and LDV, can only measure the local volume fraction and velocity at a point. The WMS and PIV techniques can obtain the multi-dimensional information of velocity and volume fraction of both liquid and gas phases in two-phase flow. The PIV measurement technique applies to low volume fractions. As the number of bubbles increases, it becomes difficult to detect bubble sizes and positions. Moreover, this technique cannot be utilised with opaque liquids as it requires a transparent test section. To overcome these problems, there is another technique which is called ultrasonic velocity profiler (UVP).

The UVP method in single-phase flow was developed by Takeda [2]. The UVP can obtain the instantaneous velocity information in a transparent and opaque liquid such as liquid metal. The only requirement for this method to be effective is that a sufficiently high number of tracer particles is suspended in the

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fluid as an ultrasound reflector [2]. When UVP is applied to two-phase flows, ultrasonic pulses are reflected from both bubbles and tracer particles. Therefore, the data measured by the UVP monitor include the velocity information of both phases. Aritomi et al. [3] developed a system to measure the velocity profiles in bubbly flows using the UVP in countercurrent flow. It was difficult to use one transducer to measure both reflectors and bubbles because they require a different configuration of the transducer. Murakawa et al. [4] measured the velocity distribution using different diameters of the transducer and developed multi-wave transducer. If a transducer diameter is selected properly, the velocity of each phase can be measured. The developed multi-wave transducer consists of two elements with different frequencies and diameters. The central element is used to measure the velocity of the liquid and outer element is used for the velocity of bubbles. A separation technique based on the difference of intensities reflected on bubbles and particles was purposed. Echo signals of the ultrasonic beam reflected by bubbles are stronger than those reflected by tracer particles. The velocity measured by the multi-wave transducer in two-phase bubbly flow has been validated by comparing with High-Speed Camera measurement by Kikura et al. [5].

In those previous studies, the UVP was used to investigate two-phase flow on one measurement line. To obtain information of multi-dimensional velocity using UVP, multiline measurement is required. Two- or three-dimensional velocity profile measurement for single phase flow by using UVP has been carried out by Kantoush et al. [6]. The application of multiple transducers has some drawbacks such as settling error and limitation of the installation position. To overcome them, an ultrasonic array sensor can be utilised as Kikura et al. [7] did in the air–water bubbly two-phase flow. An array sensor was used to measure the instantaneous and average velocity profile of single and two-phase flow by Kikura et al. [7]. It was a measurement of one-dimensional velocity. Hamdani et al. [8] developed a new approach to obtain two-dimensional velocity, and the approach was applied to single-phase and bubbly two-phase swirling flow. In the present study, two-dimensional UVP was applied to bubbly column flow, and results were compared with the PIV measurement results to assess the accuracy of the measurement system with array sensors.

The UVP method is based on pulsed ultrasound echography [9]. An ultrasound pulse is emitted from the transducer (TDX) along the measuring line, and the same transducer receives the echo reflected from the surface of tracer particles, bubbles, etc. The pulse reflection from these particles is recorded in an echo signal. The echo signal is Doppler-shifted according to reflector's velocity. Therefore, the velocity of the tracer particle can be obtained by analysing several successive reflections. During the measurement, a pulse is emitted in the interval, which corresponds to a pulse repetition frequency. Several echo sequences are needed to obtain a velocity profile, at least 2 and typically 128 sequences. The distance x between each measurement volume and TDX can be calculated from the time delay T and sound velocity c as

$$x = \frac{cT}{2}. \tag{1}$$

Since the Doppler shift of the received echo signal is proportional to the velocity, the velocity is reconstructed as

$$v = \frac{cf_D}{2f_0}, \tag{2}$$

where f_0 is basic frequency of transducer. The signal processing to detect the Doppler shift frequency f_D is the main part of UVP method. To find out the Doppler shift frequency, many signal processing methods have been developed, e.g. Ref. [10].

Originally, the UVP only measures one-dimensional velocity profile. For two-dimensional flow mapping, it is necessary to measure two velocity components at one spatial point in order to form a vector. Two velocity components are known at any intersection of measuring lines of any two transducers. An example of a two-dimensional flow mapping by two transducers is represented in Fig. 1, where, u_1 and u_2 are velocity components that are measured directly by individual transducers.

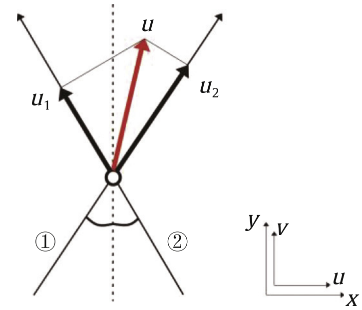

Fig. 1. Vector decomposition based on two measurement lines.

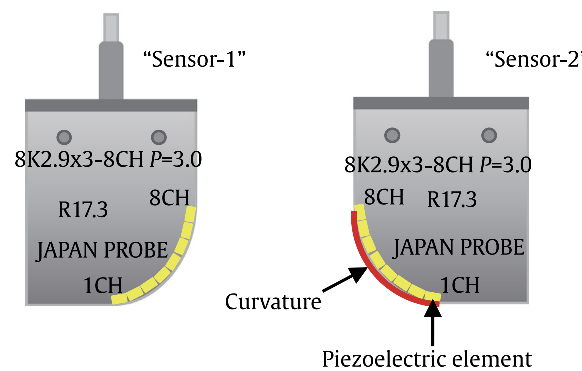

Fig. 2. The arrangement of sectorial array sensors.

Table 1
Specification of array sensor.

Basic frequency (MHz)	8
Number of element	8
Wavelength (mm)	0.19
Element size (mm×mm)	2.9 × 3.0
Pitch (mm)	3
Curvature (mm)	17.3
Height (mm)	45
Width (mm)	35
Thickness (mm)	22

$$u_1 = u \cdot n_1 = \begin{pmatrix} u \\ v \end{pmatrix} \cdot \begin{pmatrix} \sin\theta \\ \cos\theta \end{pmatrix} = u\sin\theta + v\cos\theta, \tag{3}$$

$$u_2 = u \cdot n_1 = \begin{pmatrix} u \\ v \end{pmatrix} \cdot \begin{pmatrix} -\sin\theta \\ \cos\theta \end{pmatrix} = -u\sin\theta + v\cos\theta. \tag{4}$$

Therefore, the velocity vector is obtained as [11]

$$u = \begin{pmatrix} u \\ v \end{pmatrix} \cdot \begin{pmatrix} \dfrac{u_1 - u_2}{2}\sin\theta \\ \dfrac{u_1 - u_2}{2}\cos\theta \end{pmatrix}. \tag{5}$$

Two sectorial array sensors were used in the present experiment as shown in Fig. 2. The specification of array sensor is described in Table 1. Since the sectorial array sensor has a unique configuration and consists of independent piezoelectric elements, it is important to evaluate the characteristics of array elements. By using a needle hydrophone method, measurement of ultrasound fields was carried out for the sectorial array sensors. Figure 3