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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

$$v = \frac{cf_\mathrm{D}}{2f_0}, \tag{2}$$

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.

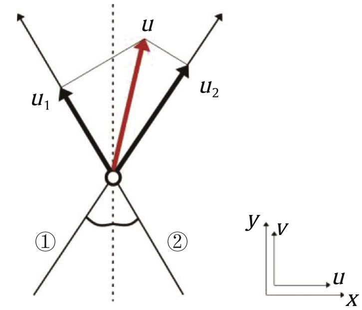

Fig. 1. Vector decomposition based on two measurement lines.

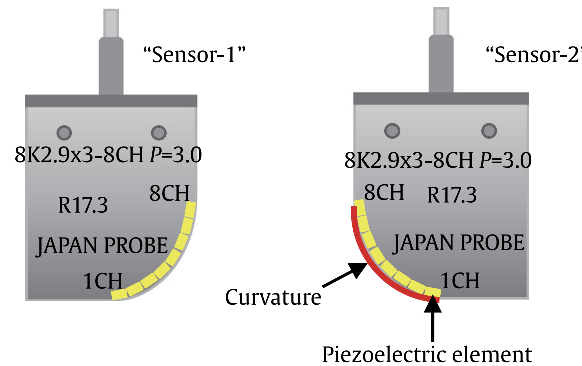

Fig. 2. The arrangement of sectorial array sensors.

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

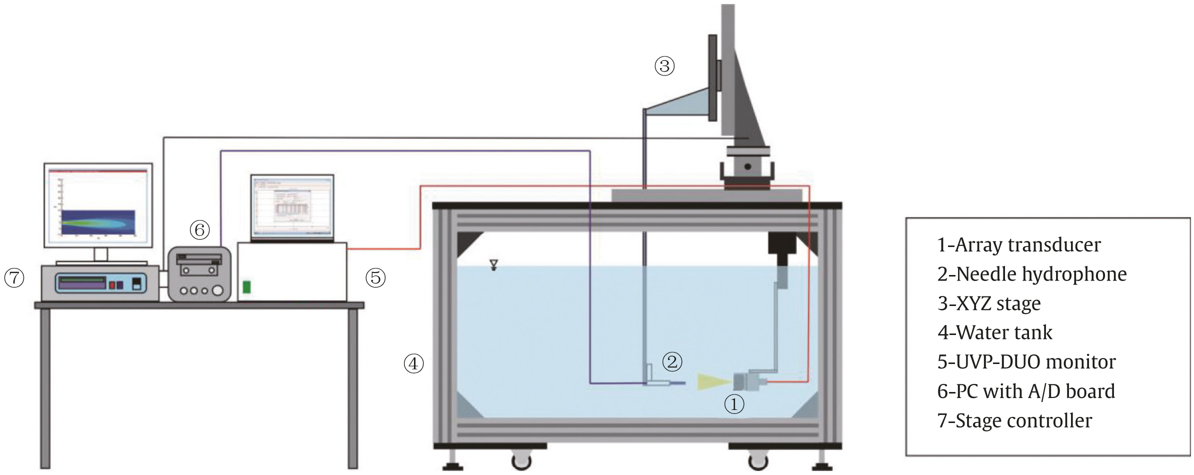

Fig. 3. The sound pressure distribution measurement system.

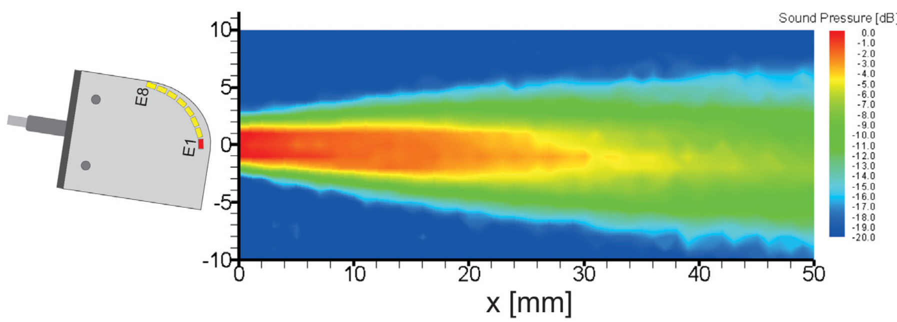

Fig. 4. Sound distribution of array sensor (Element 1 of the Sensor-1).

shows sound pressure measurement system. This system consists of an automatic *XYZ* axis stage which is installed on top of the water tank, a stage controller (Sigma Kiko Co., Ltd.) and a personal computer (PC) with A/D converter. The *XYZ* stage is controlled with the PC. The sectorial array sensor was connected to the UVP-DUO (UVP-DUO MET-FLOW Lausanne Switzerland) which generated a pulse. An ultrasonic hydrophone was traversed by the *XYZ* stage to measure the ultrasonic signal according to created grid (see Fig. 4). The signals from hydrophone were recorded by the A/D converter, with a sampling rate of 100 MS·s^{-1}. A maximum and a minimum value were averaged over 100 ultrasonic pulses. The peak-to-peak between the maximum and minimum of the received signal was considered as the ultrasonic signal-intensity at the point. The resolution of the measuring point was set at 1 mm. The total number of measuring points was 1071 with 21 (radial direction) ×51 (longitudinal direction).

Figure 4 is an example of the measurement result of sound pressure distribution for element-1 of "Sensor-1" array sensor. The sound pressure distribution measurement was performed for all the elements of both array sensors. From measured sound fields, the intensity of transmitted beam along the centre line was estimated as shown in Figs. 5 and 6. The sound intensity decreases with increasing distance from the array sensors and variation of beam intensity was measured within −10 dB until 50 mm.

A simultaneous measurement was carried out by UVP and high-speed camera (HSC). The experimental configuration and flow conditions are presented in Fig. 7 and Table 2, respectively. An acrylic rectangular box (300 mm wide, 300 mm deep and 300 mm high) was used due to high transparency for the HSC (FastCam SA5 model 1300K-M3) measurement in the present experiment. Tap water was utilised as a liquid and its level was the 280 mm

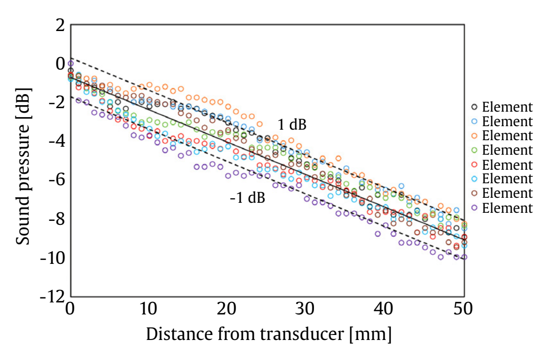

Fig. 5. Axial ultrasonic beam intensity of Sensor-1.

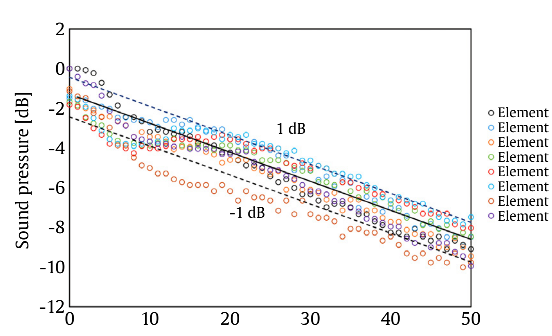

Fig. 6. Axial ultrasonic beam intensity of Sensor-2.

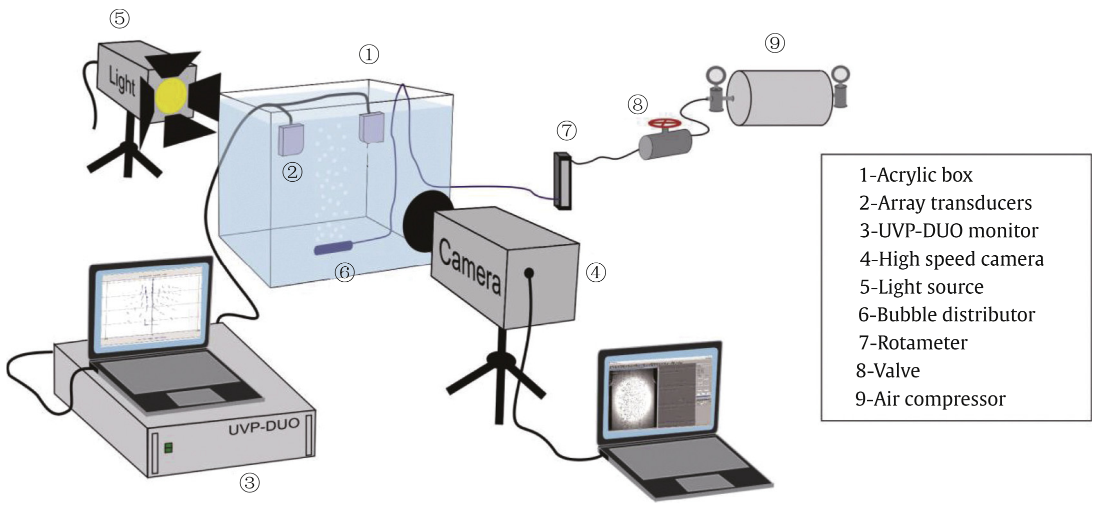

Fig. 7. Schematic diagram of experimental apparatus.

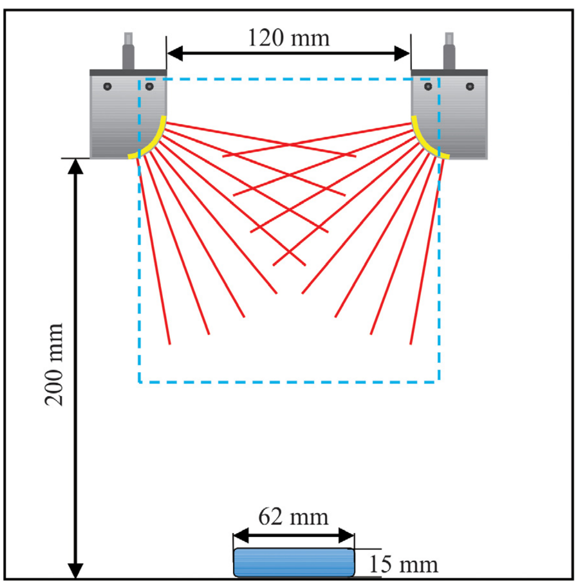

Fig. 8. Test section.

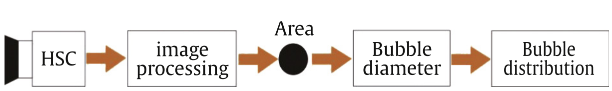

Fig. 9. Schematic of image processing for bubble distribution.

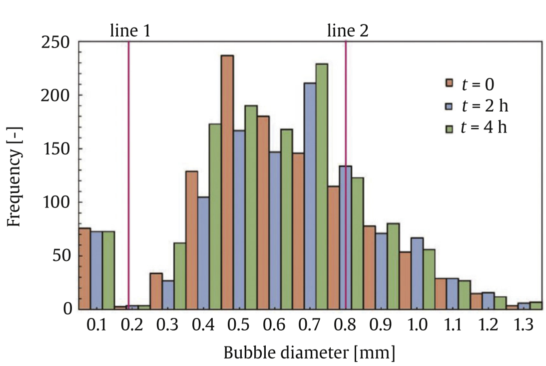

Fig. 10. Bubble diameter distribution during the whole experiment.

Table 2
Flow condition.

Working fluid	Tap water (liquid), air (gas)
System pressure	Atmospheric pressure
Water temperature (°C)	8–9
Bubble diameter (mm)	0.1–1.3
Gas flow rate ($l \cdot min^{-1}$)	0.2

high. Two sectorial array sensors were placed inside the bubble column at the height of 200 mm of height from the bottom wall, the distance between two transducers was 120 mm (see Fig. 8). Both were controlled by UVP-DUO monitor. The HSC and a light source were placed perpendicular to the box to record image sequence of the bubble motion. A porous material, 62 mm of length and 15 mm of diameter, was utilised as a gas distributor and placed at the centre of the box (see Fig. 8). The air flow rate through the gas distributor was measured by a rotameter (P200 Tokyo Keiso) and controlled by the control valve. Measurement range of the rotameter is from 0.2 to 2 $l \cdot min^{-1}$ and accuracy of the flow meter is ±3%.

Figure 8 illustrates measurement sections of the UVP and PIV in detail. The red lines represent measurement lines of the UVP. A dotted blue line represents the edge of the one image taken by HSC. An image resolution was 896 × 896 pixels. A ruler attached on the Sensor-2 for calibration of PIV measurement.

The UVP method only measures echo from reflecting particles or bubbles which are suspended in the fluid. Theory of ultrasound reflection on particles suggests that reflecting particles should have a diameter larger than $\lambda/4$, where λ is the wavelength of the emitted ultrasound burst [12]. The wavelength calculated from the relation between the basic frequency of sensor and the sound speed, as 0.19 mm. The reflected echo from particles or bubbles will be weak unless bubble diameter meets the above requirement. On the other hand, it is well known that small bubbles rise along a rectilinear path when the equivalent radii are less than 0.81 mm [13]. Bubble diameter distribution measurement was tested by HSC at different flow rate of 0.2, 0.4 and 0.6 $l \cdot min^{-1}$. Based on the average diameter and movement path of bubbles, the flow rate 0.2 $l \cdot min^{-1}$ is selected for this experiment. Figure 9 illustrates a procedure of obtaining the bubble distribution from images taken by HSC. The MATLAB algorithm is used to separate background and bubbles for an image taken by HSC. Figure 10 illustrates the bubble distribution at different times of the whole experiment with 0.2 $l \cdot min^{-1}$ gas flow rate. The bubbles with diameter of 0.3 mm to 0.81 mm were dominant as shown in Fig. 10. Because of bubble

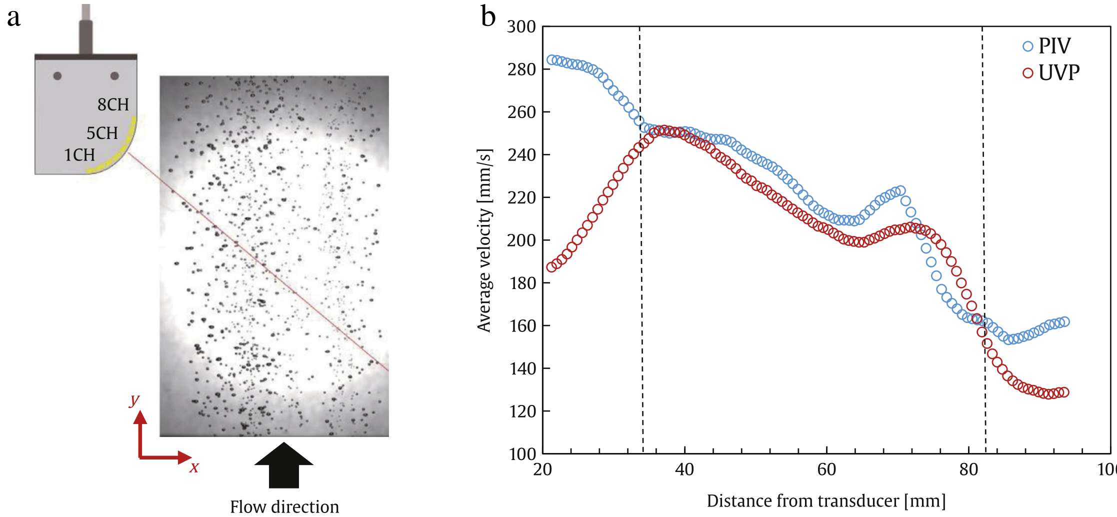

Fig. 11. (a) One-dimensional measurement by Element 5 of "Sensor-1", (b) Measurement of rising velocities of bubbles by UVP and PIV.

break-up and coalescence, bubbles smaller than the wavelength (line-1 on Fig. 10) as well as larger than 0.81 mm (line-2 on Fig. 10) were also observed which are generated in near inlet and another part of bubble sparger in this experiment. The effect of these bubbles on the experiment result is explained.

Figure 11(a) represents one-dimensional measurement performed by Element 5 of "Sensor-1". A red line represents measurement line of the UVP. Figure 11(b) showed the measurement result of the UVP and compared with the PIV result. The array sensors were placed at some distance away from the flow to minimise the disruption of the main bubbly flow (see Fig. 11(a)). The PIV measurement also started from around 20 mm, therefore the horizontal axis of Fig. 11(b) started from 20 mm. As explained in the previous section bubble diameter distribution during the whole experiment was larger than 0.81 mm in the both side of bubble sparger. The measured average velocity by the UVP is lower than the PIV result in two regions from 20 to 33 mm as well as from 85 to 93 mm. Because, first, large bubble travelled faster

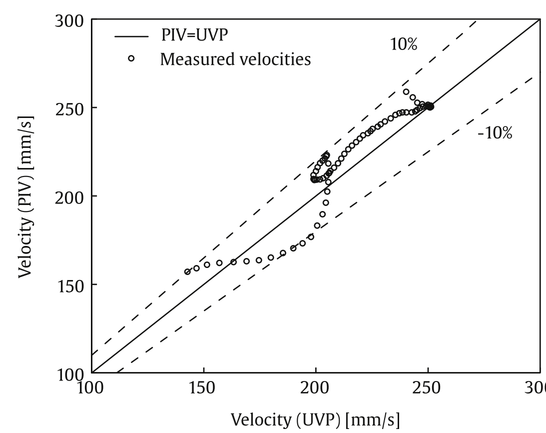

Fig. 12. Measurement of rising velocities of bubbles by UVP and PIV.

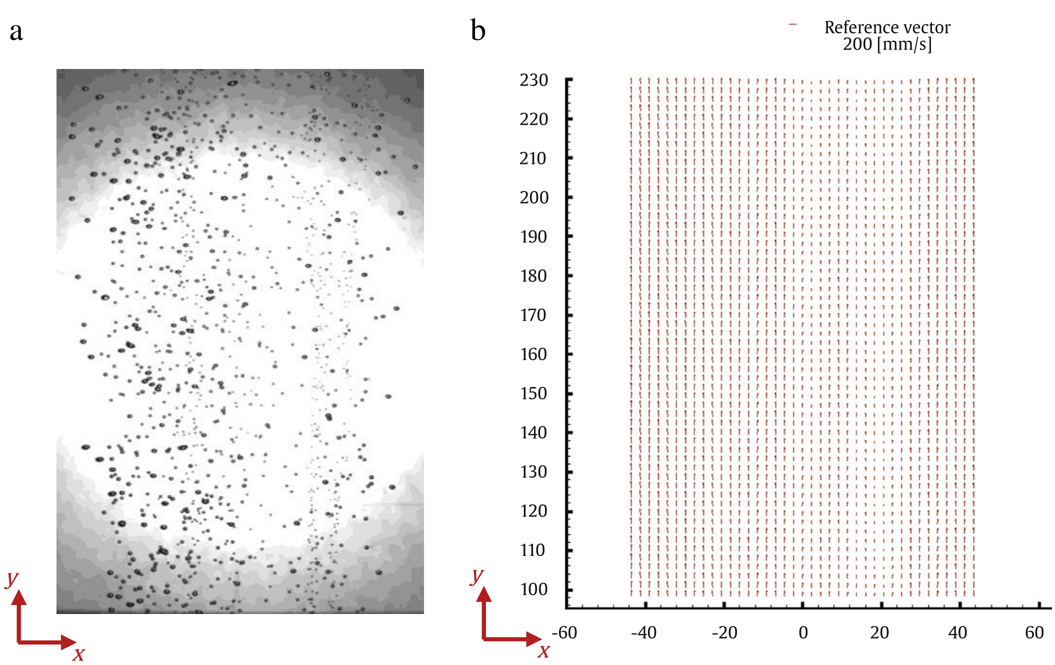

Fig. 13. (a) Example of bubble column picture. (b) PIV results of the flow conditions shown in (a).

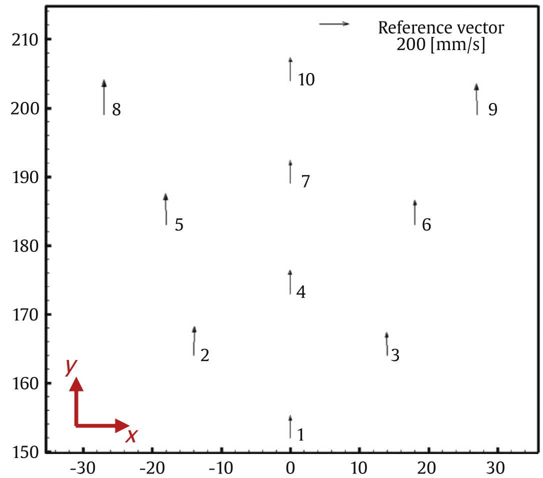

Fig. 14. Flow mapping by UVP.

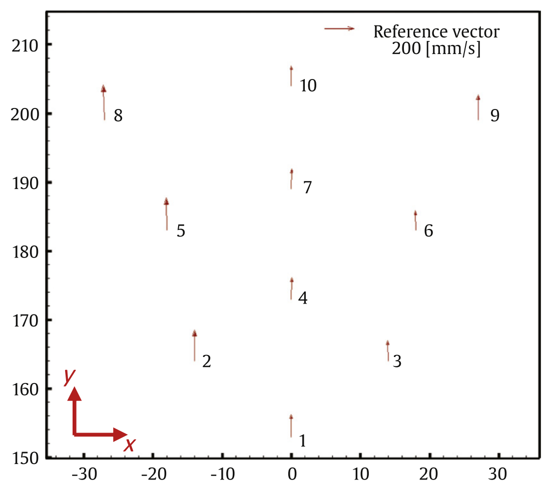

Fig. 15. Velocity vectors by PIV (Vectors at same positions with UVP result.)

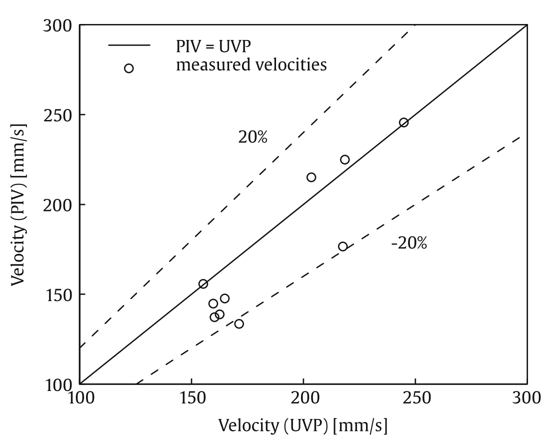

Fig. 16. Comparison of 2-D velocities along main flow direction (y-direction).

than small bubble. Second, the movement of bubbles which have a diameter larger than 0.81 mm is not rectilinear. It means that larger bubbles were sometimes crossing measurement line of UVP, sometimes not. On the other hand, the HSC measurement can detect all the bubbles during the whole experiment. Thus, the

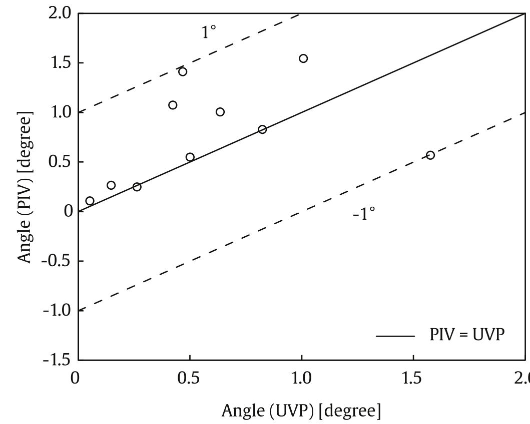

Fig. 17. Angle difference between velocity vectors.

Table 3
Parameters of UVP.

Parameters of UVP	
Channel distance (mm)	0.72
Channel width (mm)	0.72
Number of cycles	8
Number of repetitions	96
Length of measurement line (mm)	93.43
Sampling time (ms)	25
Sound velocity ($m \cdot s^{-1}$)	1443

measured velocity profile by the UVP is lower than the PIV result in those regions. The deviation between measurements was 50% and 20%, in the inlet and another part of sparger, respectively. In the range between 33 and 85 mm, the bubble diameter was smaller than 0.81 mm, and movement of bubbles was straight. In this region, the average velocities were less than 10% different from the PIV result as demonstrated in Fig. 12. It should be reminded here that the bubble sparger has 15 mm diameter and shape of a cylinder. The measurement was performed at the centre of sparger by UVP. The measurement volume of UVP is $0.72 \times 2.9 \times 3$ mm^3. It means that the UVP measured bubbles only at this volume along measurement line. The HSC took into account all of the bubbles, and the PIV algorithm estimated the velocity based on a larger measurement volume. The difference of measurement volume affected this measurement.

Figure 13(a) shows an example of bubble column image. Figure 13(b) shows the PIV result for the flow conditions shown in Fig. 13(a). The HSC camera (896×896 pixel, 500 fps) providing a resolution of 0.15 mm/pixel, was used to record images of the flow. In this way, only 134.4 cm long part of the column was recorded since it represents the most interesting part of the column. The PIV was performed with the use of MATLAB [14]. Image sequences of the bubble motion were recorded and PIV processing was used to determine the average bubble velocity from these sequences. Illumination from the rear was used to obtain bubble shadows over a large area of the column. Binary images of bubbles were obtained by applying a threshold (MATLAB algorithm) to the greyscale images and velocities were obtained from the subsequent images using PIV. Interrogation areas of 60×30 pixels in the first pass, 30×15 pixels in the second pass were used with a 50% overlap. Velocities were obtained by averaging 3000 subsequent images of the bubble motion.

For UVP flow mapping, it is necessary to measure two velocity components at one spatial point to form a vector. Two velocity components are known at any intersection of measuring lines of any two transducers. The flow mapping by UVP is shown in Fig. 14 and experimental condition is listed in Tables 2 and 3.

Table 4
Quantitative comparison of velocities measured with the UVP and PIV.

Measurement points	UVP		PIV	
	u_x (mm·s^{-1})	v_y (mm·s^{-1})	u_x (mm·s^{-1})	v_y (mm·s^{-1})
1	0.4	155.3	0.7	155.8
2	5.6	203.5	2.1	215.1
3	−2.3	159.8	−2.1	144.8
4	−2.9	164.9	4.0	147.6
5	−0.2	218.5	−0.4	224.9
6	1.9	171.3	−2.3	133.6
7	−1.2	162.6	2.6	138.9
8	2	244.8	−6.0	245.5
9	−1	217.6	0.8	176.6
10	1.4	160.3	1.3	137.2

From flow mapping by PIV, velocity vectors are selected at same positions with UVP to compare, and the vectors are shown in Fig. 15. The difference between two-dimensional velocities measured along main flow direction by PIV and UVP is less than 20% as shown in Fig. 16. Figure 17 shows the angle difference between two vectors at same position. The quantitative comparison of velocity measurement results by the UVP and PIV summarized in Table 4.

Two ultrasonic sectorial array sensors were applied to measure one- and two-dimensional velocity of bubbly two-phase flow in the rectangular bubble column. The ultrasound pressure distributions of developed array sensors were investigated to understand the ultrasonic beam characteristics. To assess measurement system with array sensors, simultaneous measurement was performed by UVP and PIV. Measurement results show that

1. The accuracy of the measurement system with array sensors was estimated as 10% for one-dimensional velocity measurement.
2. The accuracy of the measurement system with array sensors was estimated as lower 20% for two-dimensional velocity measurement.
3. Flow direction or angle deviation of two vectors at the same position measured by UVP and PIV were estimated less than 1°.

References

[1] R.C. Chen, L.S. Fan, Particle image velocimetry for characterizing the flow structure in three-dimensional gas-liquid–solid fluidized beds, Chem. Eng. Sci. 47 (1992) 3615–3622.

[2] Y. Takeda, Development of an ultrasound velocity profile monitor, Nucl. Eng. Des. (1991) 277–284.

[3] M. Aritomi, S. Zhou, M. Nakajima, Measurement system of bubbly flow using ultrasonic velocity profile monitor and video data processing unit, J. Nucl. Sci. Technol. 33 (1996) 12915–12923.

[4] H. Murakawa, H. Kikura, M. Aritomi, Application of ultrasonic doppler method for bubbly flow measurement using two ultrasonic frequencies, Exp. Therm Fluid Sci. 7 (2005) 843–850.

[5] H. Kikura, H. Murakawa, M. Aritomi, Velocity profile measurements in bubbly flow using multi-wave ultrasound technique, Chem. Eng. Commun. 172 (2009) 114–133.

[6] S.A. Kantoush, G. De Cesare, J.L. Boillat, et al., Flow field investigation in a rectangular shallow reservoir using UVP, LSPIV and numerical modelling, Flow Meas. Instrum. 19 (2008) 139–144.

[7] H. Kikura, T. Hayashida, D. Ito, et al., Application of linear ultrasonic array transducer to two-phase flow measurements, in: The 6th International Symposium on Ultrasonic Doppler Methods for Fluid Mechanics and Fluid Engineering, 2008, pp. 95-98.

[8] A. Hamdani, T. Ihara, H. Kikura, Experimental and numerical visualizations of swirling flow in a vertical pipe, J. Vis. 19 (2016) 369–382.

[9] Y. Takeda, Velocity profile measurement by ultrasonic Doppler shift method, Int. J. Heat Fluid Flow 7 (1986) 313–318.

[10] C. Kasai, K. Namewaka, A. Koyano, et al., Real-time two-dimensional blood flow imaging using an autocorrelation technique, IEEE Trans. Sonics Ultrason. 3 (1985).

[11] "UVP Monitor - User's Guide" Model UVP-DUO with Software Version 3, Met-Flow.

[12] Y. Takeda, Ultrasonic Doppler Velocity Profiler for Fluid Flow, Springer, Japan, 2012.

[13] Hassan Abdulmouti, Bubbly two-phase flow: Part I- Characteristics, structures, behaviours and flow patterns, Amer. J. Fluid Dynam. 4 (2014) 194–240.

[14] W. Thielicke, E.J. Stamhuis, PIVlab-towards user-friendly, affordable and accurate digital particle image velocimetry in Matlab, J. Open Res. Softw. 1 (2014) e30.