Evaluation of gas-liquid two-phase flow in a large pipe using Wire-Mesh Sensor

Taizo Kanai[1,*], Masahiro Furuya[1], Takahiro Arai[1], Yoshihisa Nishi[1]

[1] Central Research Institute of Electric Power Industry, Tokyo, Japan
*corresponding author: t-kanai@criepi.denken.or.jp

Abstract Wire-Mesh Sensor (WMS) was developed at the Forschungszentrum Rossendorf (FzR) in Germany. The WMS can acquire a cross-sectional distribution of void fraction. The authors has proposed an algorithm to estimate the three-dimensional individual bubble-velocity using bubble tracking with WMS. The algorithm was demonstrated for the air-water two-phase flow in a vertical round pipe at the Central Research Institute of Electric Power Industry (CRIEPI). There are two pipes: i.d.224 mm and 500 mm pipes.
Keywords: Wire-Mesh Sensor (WMS), two-phase flow, air water

1 Introduction

Recent advances in computing capability have enabled computational fluid dynamics (CFD) codes to calculate a multi-dimensional two-phase flow. Therefore, an accurate experimental database on a three-dimensional two-phase flow is crucial to validate such CFD codes. Extensive studies of the characteristics of a two-phase flow have been used to address simple experimental correlations. Several measurement techniques have also been used successfully to measure two-phase flow dynamics. Optical methods such as particle image velocimetry (PIV) and particle tracking velocimetry (PTV) on the basis of high-speed camera images are non-intrusive, but are only applicable for low void fractions. An ultrasonic velocity profile monitor (UVP) (Aritomi et al., 2000) and a void probe sensor (Hogsett et al., 1992) acquire information as one-point. A quick closing valve method acquires information as time-averaged. Therefore, these methods are difficult to measure three-dimensional measurement of the two-phase flow at high temporal and spatial resolutions. Prasser et al. (1998) had developed a wire-mesh sensor (WMS) to measure void fractions at high temporal and spatial resolutions. The WMS can acquire a local void fraction with principles based on local electrical conductivity measurement as well as measuring phasic velocity distribution by investigating the signal time-delay between two WMSs using cross-correlation analysis (Weerin et al., 2003, Prasser et al., 2002 and Richter et al., 2002). However, such phasic velocity measurement was limited to one-dimensional axial velocity, although two-phase flow in a large diameter pipe exhibits three-dimensional complex behavior by nature. It is of importance to estimate the three-dimensional phasic velocity to improve the three-dimensional two-phase flow analysis codes. Furthermore, Prasser et al. proposed methods for investigating the flow evolution using WMS. The mechanism of bubble coalescence, break-up and lateral lift force was clarified by decomposing the void fraction according to the bubble size classification (Prasser et al., 2002 and Manera et al., 2006). The authors (Kanai et al.,2012) proposed an algorithm which measures the three-dimensional gas-phasic velocity according to bubble scale. In this algorithm, bubbles are classified into certain groups via wavelet analysis and three-dimensional gas-phasic velocity is measured by a multi-point cross-correlation analysis. The multi-point cross-correlation analysis is cross-correlation analysis between a point of upstream WMS and 21×21 points of downstream WMS.

In this study, the authors propose an algorithm to estimate the three-dimensional individual bubble-velocity using bubble tracking. The proposed algorithm first identifies each bubble in the WMS signals. The alogorithm matches a pair of bubble on two WMS plane according to the bubble size and location. The validity of this method is demonstrated for a swirl flow. The proposed method can successfully visualize a swirl flow structure.

Nomenclature			
D	Pipe diameter [mm]	*Greek symbol*	
D_B	Bubble diameter [mm]	ε	Void fraction, [dimensionless]
j_G	Superficial gas velocity [m/s]		
j_L	Superficial liquid velocity [m/s]	*Subscripts*	
j_T	$j_G + j_L$ [m/s]	1st	1st WMS
L	Length scale [mm]	2nd	2nd WMS
L_{WMS}	Distance between 1st and 2nd WMS	B	Bubble
u_G	Bubble velocity [m/s]	C	Center of mass coordinate
Δt	sampling period [msec]	G	Gas
V	Volume [mm^3]	i, j, k	Position index of the matrix
x_c, y_c, t_c	Center of mass coordinate	L	Liquid
Δx, Δy	Grid gap of the WMS [mm]	WMS	Wire-Mesh-Sensor
u_G	Bubble velocity [m/s]		

2 Experimental arrangements

The WMS was developed at the Forschungszentrum Rossendorf (FzR, Germany) and consists of a pair of parallel wire layers located at the cross section of a pipe. Both the parallel wires cross at 90° with a small gap and each intersection acts as an electrode. The WMS allows the measurement of the instantaneous two-dimensional void-fraction distribution over the cross-section of a pipe, based on the difference between the local instantaneous conductivity of the two-phase flow. For a two-phase flow, the water phase shows slight conductance, while the gas phase acts as an insulator. During the signal acquisition, one plane of the electrode wires is used as a transmitter and the other as a receiver plane.

Table 1 shows test conditions of the 500 mm and the 224 mm test facility. The former is static water condition and the latter is flowing water condition. Bubble volume (size) distribution in the 500 mm pipe is measured by 500 mm WMS. This 500 mm WMS consist of 128 × 128 parallel wires, a gap of 2.8 mm. The distance between the wires (horizontal gap) is 3.9 mm. Diameter of the wires is 0.25 mm, with negligible influence on the flow field and sufficient intensity. The distance between two layers of the sensor is 40 mm. WMS is installed at z = 2,000 mm downstream from the air nozzle (L/D = 4.0). Measurement frequency and time is 1,000 frames/sec and 5 sec respectively. The 500 mm test section conducted test follow condition; water flow rate is 0 L/min (static water, superficial liquid velocity j_L = 0 m/s), and maximum air flow rate is 1500 L/min (superficial gas velocity j_G = 12.7 cm/s).

Bubble volume (size) distribution and bubble velocity in the in the 224 mm pipe is measured by 224 mm WMS. Fig. 1a shows a schematic view of the WMS used in this study. This 224 mm WMS consist of 64 × 64 parallel wires, with both layers are crossed at 90° and a gap of 2.8 mm. The distance between the wires (horizontal gap) is 3.5 mm, which represents the spatial resolution in the horizontal direction of the sensor. Fig. 1b shows cross-sectional measurement signal of the two-phase flow. The diameter of the wires was 0.25 mm, with negligible influence on the flow field and sufficient intensity. The distance between two layers of the sensor is 40 mm. The sampling frequency of such device is set to 1000 fps.

Fig. 2a shows a schematic view of the test facility, which mainly consists of a water circulation pump, air compressor, air receiver tank, air-water separation tank, heat exchanger and a test pipe. The test section consists of a PVC pipe (i.d. 224 mm), while the total height of the facility is about 6 m. The straight run pipe upstream of the WMS is 20.3 D and downstream 3.7 D where D (mm) is the inner diameter of the pipe. Fig. 2b shows a schematic view of the air injector. In order to measure the developing two-phase flow, the test section has sixteen air-injection nozzles (i.d. 10 mm) on the circumference 14.3 D, 10.7 D, 7.14 D, 3.57 D and 1.78 D upstream of WMS. Experiments are performed in an air-water system. Water is passed through an ion-exchange resin and supplied to the test section via the lower plenum by the circulating water pump. Air is supplied to the test section through the air receiver tank with the air compressor and with the air receiver tank used to control the inlet pressure alteration. In the downstream part of the test section, air and water were separated at the separation tank, the separated air is discharged into the atmosphere and the separated water was recirculated into the water tank. Water flow rate is 1500 L/min (superficial liquid velocity j_L = 0.63 m/s) and maximum air flow rate is 1500 L/min (superficial gas velocity j_G = 0.63 m/s). The water temperature is maintained at 30 degrees Celsius by the heat exchanger. The water flow rate is measured by a magnetic flow meter (KEYENCE full-duplex-UH 100H) and controlled by regulating and bypass valves. The airflow was measured by 16 mass flow meters (Yamatake Co. Ltd., MCF015) and controlled by the air supply system. Table 1shows the flow conditions and the measurement setup of the WMS.

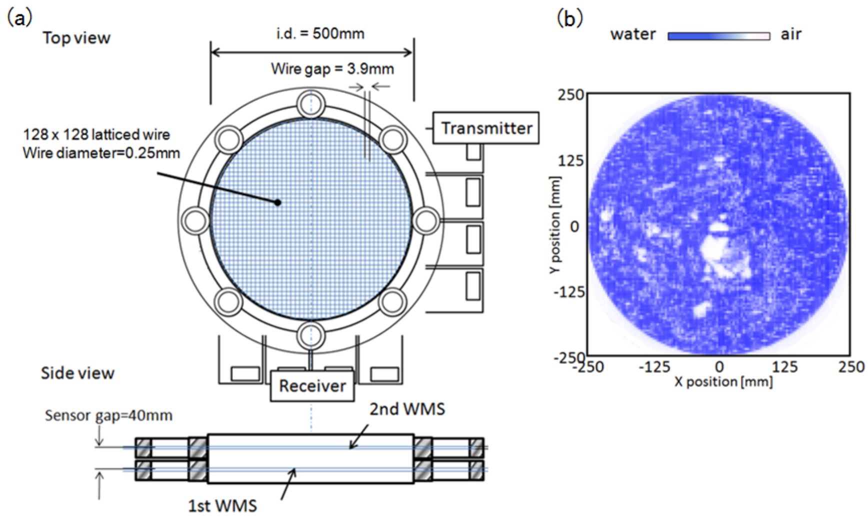

Fig. 1a (left) Schematics of 500mm WMS. Fig. 1b (right) Cross-sectional measurement of the two-phase flow.

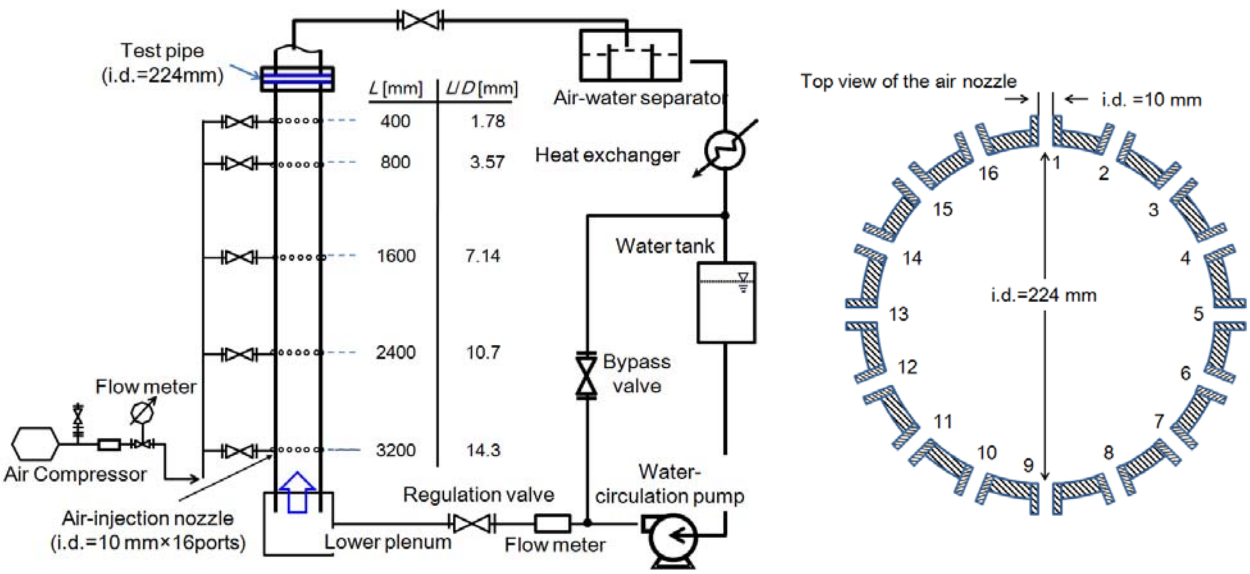

Fig. 2 a (left). Schematic of the 224 mm test facility. Fig. 2 b (right): Schematic of the air-injector nozzle.

Table 1 Test conditions of the 224 mm and the 500 mm test facility.

	500 mm test	224 mm test
Test pipe diameter	500 mm	224 mm
Water flow rate, j_L	0 L/min, 0 m/s (stagnant)	1500 L/min, 0.63 m/s
Gas flow rate, j_G	1500 L/min, 12.7 cm/s	1500 L/min, 0.63 m/s
Pressure and temperature	Normal pressure and temperature	Normal pressure and temperature
WMS diameter	500 mm	224 mm
WMS channel	128 × 128	64 × 64
Wire gap, Wire diameter	3.9 mm, 0.25 mm	3.5 mm, 0.25 mm
Testing	Bubble volume	Bubble volume and velocity
Method	Bubble identification	Bubble identification and tracking

3 Bubble identification and tracking

Two-phase flow data consist of a three-dimensional matrix 64 × 64 × 5000 ($i \times j \times k$). Each of these data contain two-dimensional void distributions of 64 × 64 WMS and 5000 time-series dataBubble is defined as a region of connected gas elementsand summation of bubble elements is given by Eq. 1.

$$S_{\mathrm{B}} = \sum_{i,j,k \in \mathrm{B}} \varepsilon_{i,j,k} \,, \tag{1}$$

where, S_{B} is the summation of bubble elements, $\varepsilon_{\mathrm{i,j,k}}$ is the void fraction at i, j, k. The center of mass coordinates (x_{c}, y_{c}, t_{c}) can be obtained by averaging the coordinates of all elements belonging to the same bubble. Moreovereach coordinates are weighted by the local void fraction (Eqs. 2-4). Then, it seeks pairs of resemble bubble in two WMS data according to the matching condition. The bubble tracking is targeting the bubbles of $S_{\mathrm{B}} \geq 50$. The tracking ranges (ΔX, ΔY) are -24.5 mm $\leq \Delta X$, $\Delta Y \leq$ 24.5 mm. The matching condition ($V_{\mathrm{B,1st}}$ / $V_{\mathrm{B,2nd}}$) whether to be the same or not same is principally $0.33 \leq V_{\mathrm{B,1st}} / V_{\mathrm{B,2nd}} \leq 3$. Three-dimensional bubble velocity is calculated as Eq. 5 by the travel distance of the center of mass (Δx_{c}, Δy_{c}, Δt_{c}).

$$x_{\mathrm{c}} = \frac{\sum_{i,j,k} j \cdot \Delta x \cdot \varepsilon_{i,j,k}}{\sum_{i,j,k} \varepsilon_{i,j,k}} \,, \tag{2}$$

$$y_{\mathrm{c}} = \frac{\sum_{i,j,k} i \cdot \Delta y \cdot \varepsilon_{i,j,k}}{\sum_{i,j,k} \varepsilon_{i,j,k}} \,, \tag{3}$$

$$t_{\mathrm{c}} = \frac{\sum_{i,j,k} k \cdot \Delta t \cdot \varepsilon_{i,j,k}}{\sum_{i,j,k} \varepsilon_{i,j,k}} \,, \tag{4}$$

$$\boldsymbol{u}_{\mathbf{B}} = \frac{\Delta x_{\mathrm{c}},\, \Delta y_{\mathrm{c}},\, L_{\mathrm{WMS}}}{\Delta t_{\mathrm{c}}} \,, \tag{5}$$

where Δx, Δy is the wire gap (3.5 mm), Δt is the sampling period (1 msec). Δx_{c}, Δy_{c}, Δt_c is the movement of the center of mass. L_{WMS} is the distance between two WMSs. L_{WMS} = 40 mm in this study. Bubble volume (V_{B}) can be calculated bythe summation of the bubble elements (S_{B}), the bubble velocity (u_{B}), the geometric structure of the WMS and the sampling period (Eq. 6). Moreover, the bubble diameter (D_{B}) is calculated by Eq. 7. Fig.3 shows the example of the bubble identification. Flow conditions j_{L} = 0.63 m/s, j_{G} = 0.63 m/s, L/D = 14.3.Sphere size means bubble size. Arrows mean bubble velocity vector.

$$V_{\mathrm{B}} = u_{\mathrm{B}} \Delta x \Delta y \Delta t \sum_{i,j,k \in \mathrm{B}} \varepsilon_{i,j,k} \,, \tag{6}$$

$$D_{\mathrm{B}} = \sqrt[3]{\frac{6 V_{\mathrm{B}}}{\pi}} \,, \tag{7}$$

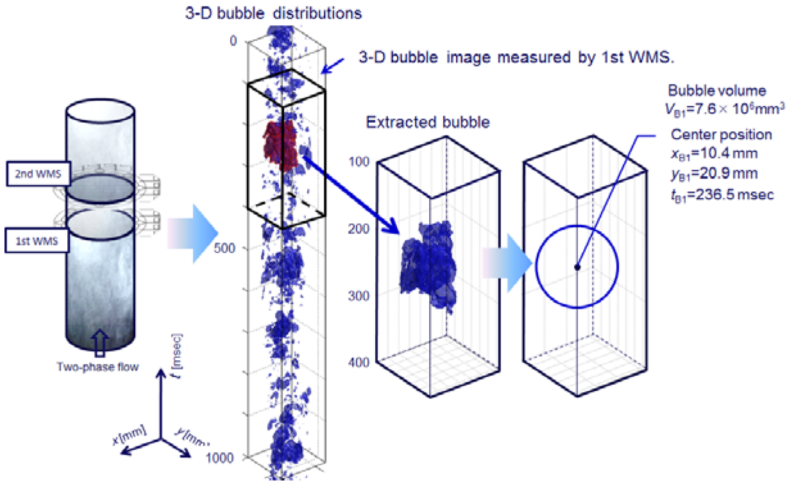

Fig. 3. Example of the bubble identification. Flow conditions j_L = 0.63 m/s, j_G = 0.63 m/s, L/D = 14.3.

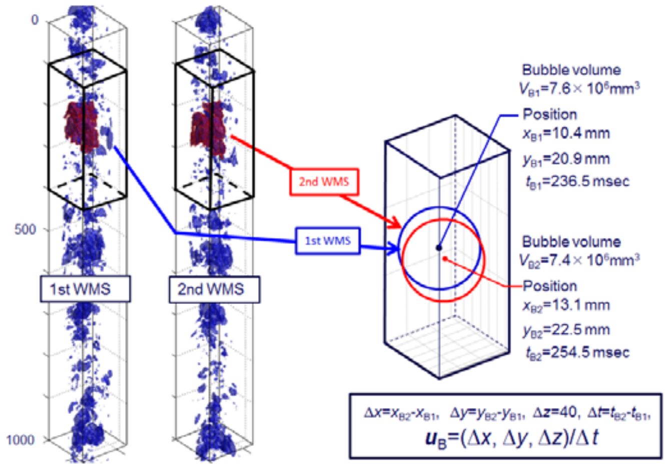

Fig. 4. Example of the bubble tracking. Flow conditions j_L = 0.63 m/s, j_G = 0.63 m/s, L/D = 14.3.

4 Results

Fig.5 shows the three-dimensional image of the two-phase flow in the 500 mm test section, j_L = 0 m/s, j_G = 1.7, 4.2, 8.4, 12.7 cm/s. Bubble number in the tow-phase flow is measured by using bubble identification method. Bubble number in 5 sec, 500 mm pipe is about 134,000 bubbles at j_G = 1.7 cm/s, 255,000 bubbles at j_G = 4.2 cm/s, 328,000 bubbles at j_G = 8.4 cm/s and 351,000 bubbles at j_G = 12.7 cm/s. Fig.7 shows the bubble size distributions. This result shows that in case of j_G = 1.7 cm/s and 4.2 cm/s small bubbles (5 – 10 mm) are dominant and the large bubbles hardly exist (> 40 mm). In case of j_G = 8.4 cm/s and 12.7 cm/s small bubbles (5 – 10 mm) are dominant, however the large bubbles exist to some extent. Fig.6 shows the three-dimensional bubble size distribution of the two-phase flow, j_L = 0 m/s, j_G = 1.7, 4.2 cm/s.

An algorithm to estimate the three-dimensional bubble velocity is developed and is applied in a measurement of developing two-phase flow. Fig.8 shows bubble velocity distributions by bubble groups in a churn flow. In order to measure developing two-phase flow, the test section has sixteen air-injection nozzles (*i.d*. 10 mm) on the circumference L/D = 1.78, 3.57, 7.14, 10.7, 14.3 upstream of WMS. In this study, bubbles are grouped into four groups. Group 1 is the bubble group of 10 mm ≤ D_B < 20 mm, Group 2 is the bubble group of 20 mm ≤ D_B< 40 mm, Group 3 is the bubble group of 40 mm ≤ D_B < 80 mm, Group 4 is the bubble group of 80 mm ≤ D_B. Fig.5 is the result of bubble velocity distributions by bubble groups in the churn flow (j_L = 0.63 m/s, j_G = 0.42 m/s). For a churn flow, Group 1 and Group 2 is the most numerically, number of bubbles of Group 3 and Group 4 is small. On the contrary, volume and the influence toward the flow dynamics is large. The peak of bubble velocity distributions differ for bubble size Group. The peak of bubble velocity distributions is as follows. For Group 1, about 0.8 - 1.2 m/s, For Group 2, about 1.2 - 1.8 m/s, For Group 3, about 1.7 - 2.4 m/s, For Group 4, about 2.4 - 3.0 m/s (differ for L/D).

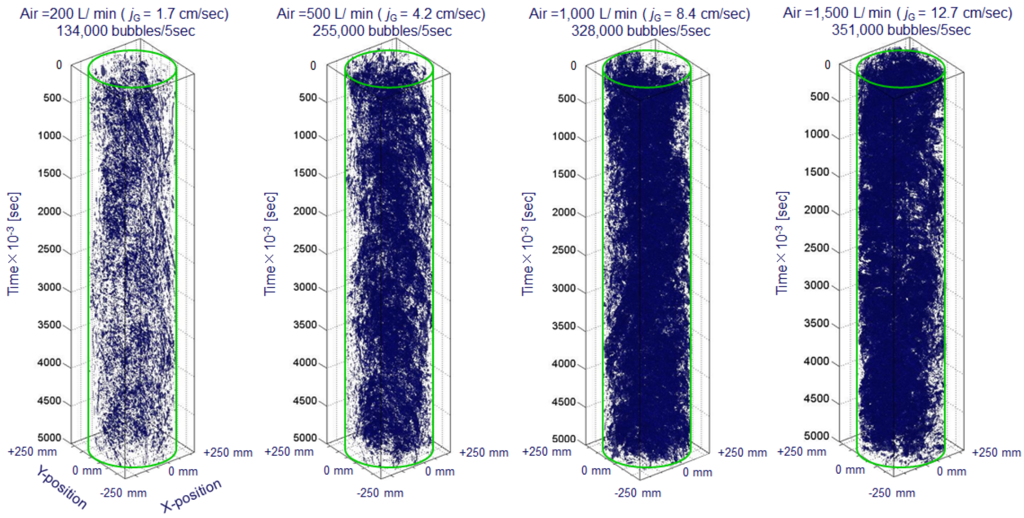

Fig.5 Three-dimensional image of the two-phase flow, j_L = 0 m/s, j_G = 1.7, 4.2, 8.4, 12.7 cm/s.

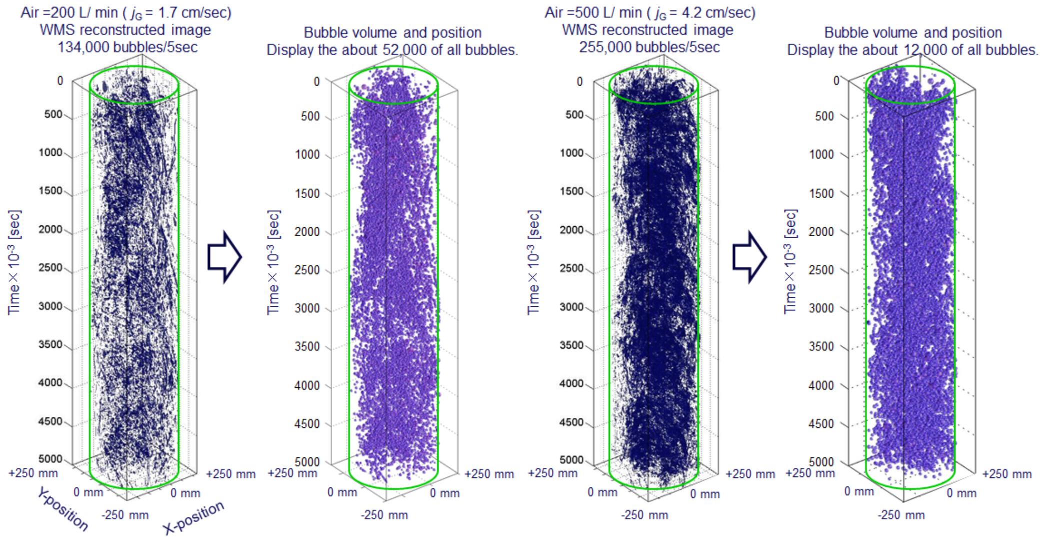

Fig.6 Three-dimensional bubble size distribution of the two-phase flow, j_L = 0 m/s, j_G = 1.7, 4.2 cm/s.

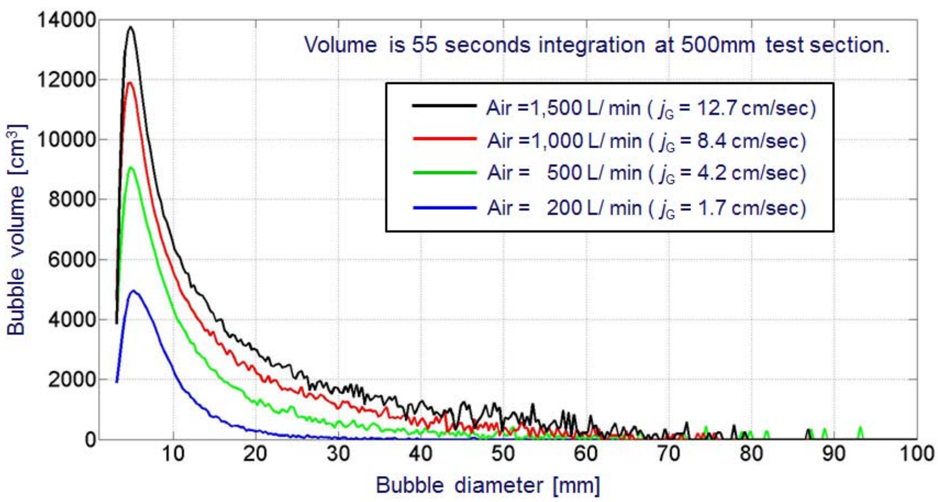

Fig.7 Bubble size distributions in 500 mm test section, j_L = 0 m/s, j_G = 1.7, 4.2, 8.4, 12.7 cm/s.

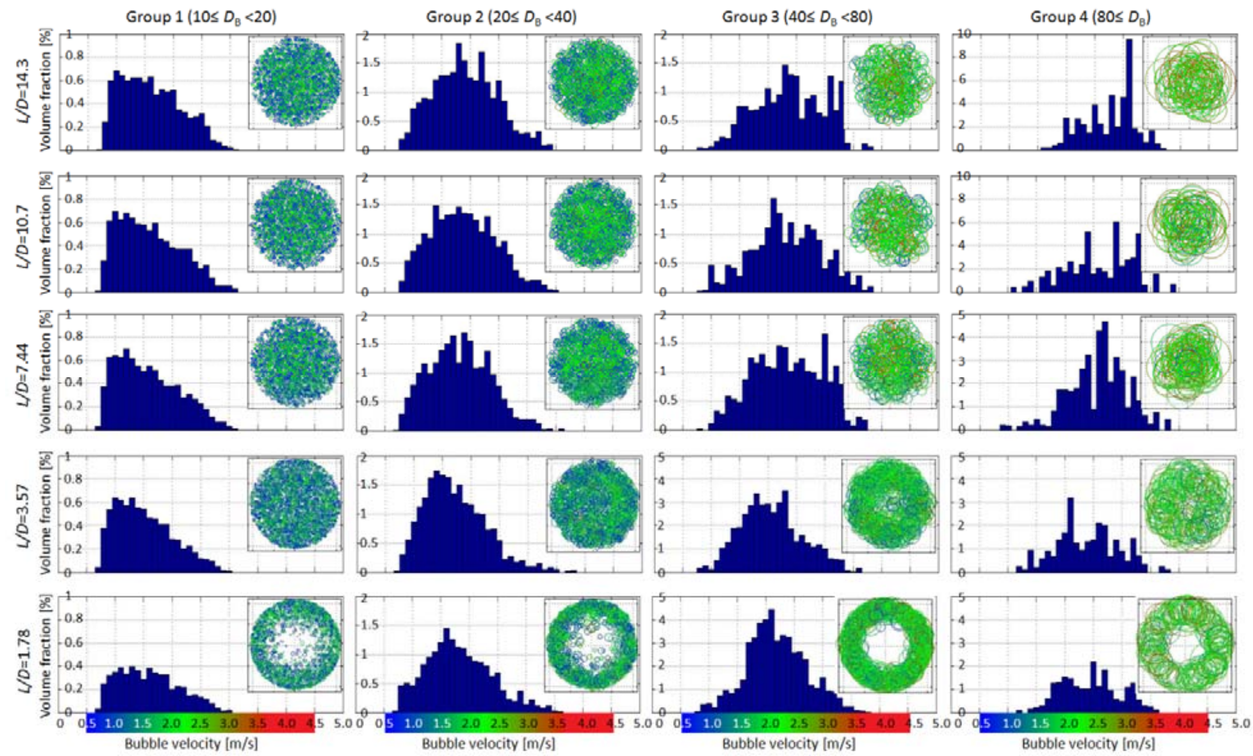

Fig.8 Bubble velocity distributions by bubble groups in a churn flow, L/D = 1.78 - 14.3, j_L = 0.63 m/s, j_G = 0.42 m/s.

5 Conclusions

An algorithm to estimate the three-dimensional bubble velocity (bubble identification and tracking method) is developed and is applied in a measurement of developing two-phase flow.

Bubble identification method is applied in a measurement of the two-phase flow in 500 mm test section. The inner diameter of the dual WMS is 500 mm (equal to the test pipe). The 500 mm test section conducted test follow condition; water flow rate is 0 L/min (static water, superficial liquid velocity j_L = 0 m/s), and maximum air flow rate is 1500 L/min (superficial gas velocity j_G = 12.7 cm/s). The bubble size distributions measured by using bubble identification method shows that in case of j_G = 1.7 cm/s and 4.2 cm/s, small bubbles (5 – 10 mm) are dominant and the large bubbles hardly exist (> 40 mm). In case of j_G = 8.4 cm/s and 12.7 cm/s small bubbles (5 – 10 mm) are dominant, however the large bubbles exist to some extent.

In order to measure developing two-phase flow, 224 mm test section which has sixteen air-injection nozzles (*i.d.* 10 mm) on the circumference L/D = 1.78, 3.57, 7.14, 10.7, 14.3 upstream of WMS is used. For the distance between the nozzle and the WMS is short (L/D = 1.78), bubbles are concentrated near the wall and the bubbles which flow toward the center is dominant. Diffusion or sheering force is act as driving force that push bubbles away from the wall. For L/D = 3.57, the bubbles of 10 mm ≤ D_B < 30 mm are substantially uniformly distributed and the bubbles of $D_B \geq$ 30 mm are still distributed in a donut shape (r> 20 mm). For L/D = 7.14, the bubbles of 10 ≤ D_B < 30 are substantially uniformly distributed and the larger bubbles are distributed central portion of the flow path.

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