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Ultrasonic Velocity Profiler for the Measurement of a Bubbly Flow Velocity Vector in Small Channels

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Abstract: The multi-dimensional velocity distribution of coolant in bubbly flow within the fuel rod bundles of the reactor core in boiling water reactors (BWRs) is elucidated by experimental investigation in this study. Since a measurement technique is required for such an investigation, this paper proposes the development of an ultrasonic velocity profiler (UVP). The combination of special ultrasonic transducers and modified signal processing on the UVP is proposed to obtain a multi-dimensional velocity vector of the bubbles and liquid in bubbly flow. The ability of the proposed technique is demonstrated by performing an experiment in swirling bubbly flow and its applicability confirmed by comparing the results with another technique. The sound pressure distribution in the narrow channel of the rod bundle is then measured prior to the verification of the ultrasonic wave emitted through a small channel. The echo signal reflected from reflectors dispersed in the liquid, bubble, and tracer particles in the small channel of the rod bundle indicates that the proposed UVP can be applied in this application with a low level of multi-reflection. Finally, the UVP system is demonstrated to measure the velocity vector of bubbly flow in the narrow flow channel on the rod bundle, and the velocity vector of the bubble and liquid obtained simultaneously.

Keywords: Ultrasonic, velocity, vector, bubbly flow

Abbreviations and Symbols

A/D	Analog and digital converter	I	Sound intensity
BWRs	Boiling water reactors	I_{max}	Maximum sound intensity
DAC	Doppler amplitude classification	k	Discrete-time
PIV	Particle image velocimetry	N_{REP}	Number of repetitions
SPL	Sound pressure level	P	Energy density of spectra in time-frequency function
STFT	Short-time Fourier transform	Q_{G}	Superficial gas velocity
SUTS	Single ultrasonic gas-liquid two-phase separation	Re_{sw}	Reynolds number based on swirling velocity
TFA	Time-frequency analysis	S_{n}	Time step
UTDC	Ultrasonic time domain cross-correlation method	S_{w}	Swirl parameter
UVP	Ultrasonic velocity profiler	U_{L}	Superficial liquid velocity

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2D	Two-dimensional	V	Velocity
a_c	Centrifugal acceleration	W_n	Window length
c	Sound velocity	V_x	Axial velocity
D(n)	Doppler signal	V_y	Tangential velocity
f_D	Doppler frequency	X	STFT spectrogram
f_0	Basic frequency	Δx	Axial resolution
G	Transmitter-receiver gap	Δy	Lateral resolution
i	Position or channel	θ	Incident angle

1. Introduction

The boiling water reactor (BWR) is a nuclear power plant with many operating units and safety is the main concern. The gas-liquid two-phase bubbly flow, which works as the coolant occurs in the reactor, exists around the sub-channel within the nuclear fuel rod bundle, and its behavior significantly influences the safety aspect of the BWR [1, 2]. Furthermore, in the reactor core, the spacer grids supporting the fuel rod bundle provide an effective mixing device by attaching flow deflectors, such as swirling vanes, installed for heat transfer enhancement between the fuel rod and coolant. The velocity distribution of the bubble and liquid, which has multi-dimensional motion, affects heat removal from the fuel to the coolant and phase distribution within the reactor core [3] [4], relating strongly to plant safety. Hence, the multi-dimensional velocity or velocity vector of the bubble and liquid distributed in the fuel rod bundle requires investigation, and a measurement technique is therefore needed.

Several intrusive techniques have been utilized to measure the velocity data in two-phase bubbly flow, such as the conductive probe [5], which is an intrusive method that disturbs the flow and leads to instrument lifetime distortion. Moreover, it cannot obtain liquid data. To eliminate these limitations, non-intrusive measurement techniques for deriving the velocity data of both phases have been proposed, such as the technique and particle image velocimetry (PIV). A radiation-based technique such as an X-ray [6] can measure the two-dimensional (2D) velocity profile of bubbles and liquid in bubbly flow. However, the velocity measurement within the rod bundle flow channel is impossible due to the rod structure appearing on the X-ray image. The PIV [7] is capable of obtaining a two-dimensional (2D) velocity profile. It requires a transparent section for the optical source emitted by the laser sheet and the capturing of the camera to obtain a 2D velocity profile at the region of interest. Whereas the flow field captured in a typical fuel rod bundle with spacer grids is obstructed optically by the rods themselves and cannot provide velocity information on bubbly flow in the full profile along the flow path of rod bundles. Therefore, the measurement technique for obtaining a multi-dimensional velocity profile in this application is pursued.

The ultrasonic velocity profiler (UVP) is a powerful method for visualizing the spatial-temporal velocity distribution in liquid flows [8]. In the UVP, the ultrasonic wave can transmit through various materials, and optical access is not required. This method is a non-intrusive measurement and can be applied to an opaque fluid. It has been applied to obtain liquid velocity profiles in several applications, such as water [9], liquid metal [10], magnetic liquid [11], and liquid sodium [12]. Furthermore, apart from the velocity profile measurement, the UVP can be applied in other fields, such as the investigation of liquid leakage in plant decommissioning work [13], measurement of the velocity structure, particle concentration profiles in opaque turbidity currents [14], and estimating the maturity and inner pulp structures of fresh fruit using the information on the Doppler velocity and echo intensity [15].

In the UVP, an ultrasonic pulse is transmitted from the transducer along the measurement line to the liquid. The same transducer derives the echo signal reflected from the moving reflector, such as a tiny particle dispersed in the fluid. When the ultrasonic pulse is emitted repeatedly, the echo signals are obtained sequentially. The Doppler signal influenced by the velocity of moving particles can be demodulated from the echo signals. The Doppler frequency f_D(i) directly relates to the velocity of the particle (i is the position or channel). Hence, the velocity of the particle at position $V(i)$ can be computed as

$$V(i) = \frac{c f_D(i)}{2 f_0} \tag{1}$$

where c is the sound velocity in fluid, f_0 means the basic frequency of the ultrasonic pulse, and θ is the incident angle. If the Stokes number on the relation between small particles and liquid < 0.1, the particle will follow the liquid streamline. Then, if particles are dispersed in the liquid, the velocity profile of the liquid can be obtained. However, the original UVP can obtain the velocity data only in one dimension.

Huther et al. [16] developed a three-dimensional velocity measurement in open-channel flow using one transmitter and four receivers, while Obayashi et al. [17] proposed a UVP system for two-dimensional measurement using one transceiver and one receiver. These techniques can obtain a multi-dimensional velocity profile. However, they are only able to measure liquid flow.

In bubbly flow, Aritomi et al. [18] proposed a hybrid system that combines the UVP measurement and video data processing unit to distinguish the velocity profile of both phases. However, a limitation in separation occurred when the velocity of both phases was not much different. Murakawa et al. [19] utilized a multi-wave TDX transducer and the time domain cross-correlation method (UTDC) to measure instantaneous liquid and bubble velocity profiles. Wongsaroj et al. [20] presented the UVP with single ultrasonic gas-liquid two-phase separation (SUTS), which relies on combining time-frequency analysis and Doppler amplitude classification. The method can measure the instantaneous velocity profile of bubbles and liquid in bubbly flow using a single frequency. The measurement accuracy was guaranteed by the good agreement of the comparison with the PIV method. The discrepancy was inside ± 10%. Nevertheless, these techniques have not been applied in multi-dimensional bubbly flow. Then, Wongsaroj et al. [21] developed the UVP method based on SUTS to integrate multiple transducers, one transmitter and two receivers, to measure a 2D velocity vector profile in open-channel flow. Nevertheless, it has not yet been applied for this purpose in a small channel with a narrow flow field like the rod bundles.

This paper presents the development of a UVP system to obtain multi-dimensional velocity distribution or velocity vector of bubbly flow in narrow areas, applicable for experimental investigation on rod bundles. The ultrasonic sound pressure distribution and echo signal reflected from the reflectors in rod bundles are investigated in this study, focusing on a two-dimensional measurement.

2. Ultrasonic Velocity Profiler for Measurement in Bubbly Flow

2.1 Single Ultrasonic Gas-Liquid Two-phase Separation (SUTS)

The phase separation algorithm plays an important role in distinguishing the gas bubble and liquid phase velocity profile. Figure 1 presents a schematic of the SUTS, which is an efficient phase separation algorithm [20]. It is inserted into the UVP system to separate the velocity data of both phases. This technique involves the integration of time-frequency analysis (TFA) and Doppler amplitude classification (DAC). Short-time Fourier transform (STFT) is selected as the time-frequency estimator, decomposing the frequency components of the Doppler signal according to the time. The frequency values of the Doppler signal can be observed from the peak energy occurring on the spectrogram in each time location, as expressed in equations (2) and (3).

$$X(k,\, f_D) = \sum_{n=0}^{N_{REP}-1} D(n) W_n (n - kS_n) \exp(-jn2\pi f_D) \tag{2}$$

$$P(k,\, f_D) = \left| X(k,\, f_D) \right|^2 \tag{3}$$

Where k is discrete-time, $D(n)$ is Doppler signal, W_n is window length, S_n is time step, and $P(k, f_D)$ represents the energy density of spectra in the time-frequency function.

Each frequency component is then classified as the Doppler frequency of particles and bubbles by comparing the value of the Doppler amplitude in that time location with the threshold value. If the amplitude value is higher than the threshold, the frequency value will be defined as the Doppler frequency of the bubble. On the contrary, if the value is lower than the threshold, the frequency value in that location will be the Doppler frequency of particles. The Doppler frequency of bubbles and liquid groups is averaged separately. The velocity value of bubbles and liquid can then be obtained separately by placing these Doppler frequencies into equation (1).

2.2 Integration of SUTS and Multiple Transducers for Two-dimensional Measurement in Bubbly Flow

To obtain a 2D velocity vector profile, multiple transducers with one transmitter and two receivers are utilized, as shown in Figure 2, known as a multi-ultrasonic element sensor system. The receivers are employed to obtain two Doppler frequencies, $f_{D1}(i)$ and $f_{D2}(i)$, respectively, from the echo signals reflected by the reflectors along each measurement channel i with a certain echo angle $\theta(i)$. The echo angle depends on the measurement distance and transmitter-receiver gap G. To minimize uncertainty, the receiving area is designed to be small. By using $f_{D1}(i)$ and $f_{D2}(i)$ in each measurement channel, the 2D velocity vector profile can be reconstructed using equations (4) to (6). To achieve the measurement in bubbly flow, the SUTS is integrated with a multi-ultrasonic element sensor system

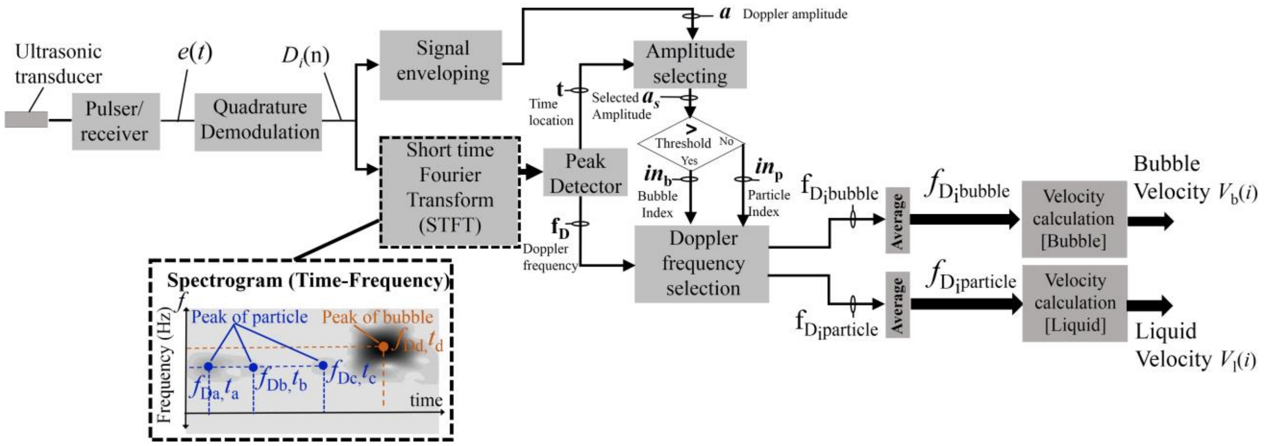


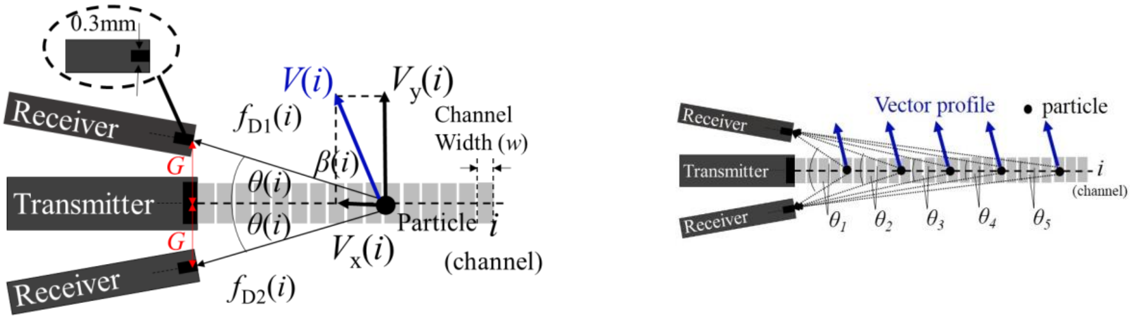
Fig. 1 - Schematic of the UVP with SUTS

and applied to the UVP. It can measure the 2D velocity vector profile of bubbles and liquid in bubbly flow. Figure 3 presents a schematic of the integrated measurement system. The sensor system is connected to the multiple-channel pulser/receiver, while the echo signals are obtained via receivers 1 and 2. The signals are amplified by the pulser/receiver. The signals are sent to UVP processing, including SUTS, to compute the velocity of bubbles and liquid (particles): $V_{\mathrm{particle1}}$, V_{bubble1}, $V_{\mathrm{particle2}}$, and V_{bubble2}. The 2D velocity of the bubbles and liquid can then be reconstructed separately by the vector reconstruction section based on equations (4) to (6).

$$V_x(i)=\frac{c}{2f_0\sin\theta(i)}\left(f_{Di}(i)-f_{D2}(i)\right) \tag{4}$$

$$V_y(i)=\frac{c}{2f_0(1+\cos\theta(i))}\left(f_{Di}(i)-f_{D2}(i)\right) \tag{5}$$

$$V(i)=\sqrt{V_X^2(i)+V_y^2(i)} \tag{6}$$



(a)

(b)

Fig. 2 - Multi-ultrasonic element sensor system (a) schematic of the measurement with a single particle; (b) image of the transducer; (c) schematic of the measurement with multiple particles

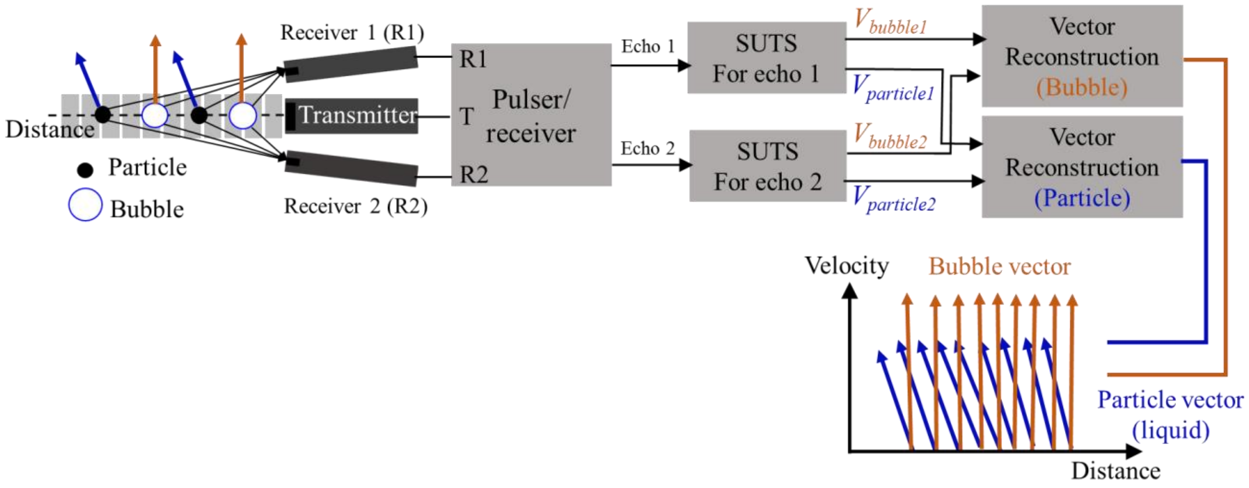


Fig. 3 - Schematic of UVP integration with SUTS and multi-ultrasonic element sensor system

3. Experimental Measurement in Swirling Bubbly Flow

In order to demonstrate the performance of the proposed UVP, the experimental measurement was executed in swirling bubbly flow. Figure 4 represents a schematic diagram of the experimental apparatus and UVP system. The UVP system consisted of a multi-ultrasonic element sensor system; one 4MHz transmitter (Model: TX-4-5-8, Imasonic, Switzerland) and two 4MHz receivers (Model: 4K5x0.3I, Japan Probe, Japan), a multiple-channel ultrasonic pulser/receiver (Model: JPR-10C-8CH3R, Japan Probe, Japan), a digitizer (Model: NI PXI-1033, National Instruments, USA), and a computer with LabVIEW software version 2011. The pulser/receiver emitted ultrasonic pulses via the transmitter and received the echo signals through receivers 1 and 2. The echo signals were subsequently received and amplified by the pulser/receiver. The digitizer converted the signals received from the pulser/receiver into a digital signal, with a sampling rate of 250 MS/s. Signal data from the digitizer was sent to the computer via a PCI port. The signal processing and velocity computation were performed using LabVIEW software. The transducers were installed in the test section (water box). The pipe was made from acrylic with an internal diameter of 20 mm. Tap water at a temperature of 12 ºC ±2 ºC dispersed with nylon particles 80 µm, and bubbles were working fluid. The water was circulated from the bottom to the top by the pump. An electromagnetic flowmeter was used to measure the water flow rate. A bubble generator was placed upstream, 50D from the test section, to generate the bubbles. A swirling motion was induced by inserting a twisted tape into the acrylic pipe. The twist ratio y was set to = 3; the same as for industrial purposes. For the UVP parameter setting, the basic frequency was f_0 4MHz with four cycles per pulse, the emitted voltage 160 Vp-p, pulse repetition frequency f_{PRF} 4 kHz, and the number of repetitions N_{REP} set at 128.

Firstly, the experiment was conducted at swirling bubbly flow at a very low void fraction. The superficial liquid velocity U_L was set at 500 mm/s, $Re_{sw} = 11252$, $a_c = 6.84$ m/s^2, and $S_w = 6496$. The gas flow rate was $Q_G < 0.06$ L/min. The bubble diameter was approximately 2–3 mm, calculated using the image processing technique on the PIV picture. The instantaneous 2D velocity vector of bubble and liquid in a swirling motion was measured by the UVP and compared with the PIV technique. Figure 5 shows the measurement results. The brown and blue vectors represent the instantaneous velocity vector of the bubbles and liquid obtained from the UVP, respectively. The black and green vectors represent the instantaneous velocity vector of the bubbles and liquid obtained from the PIV, respectively. The velocity vector of both phases could be separated instantaneously. As can be observed, the 2D velocity derived from both techniques exhibits a similar trend. Moreover, the 2D vector of the bubbles and liquid representing the swirling effect can be observed. These can guarantee the measurement ability of the proposed UVP.

An experiment was then conducted in swirling bubbly flow at different airflow rates Q_G: 0.1, 0.2, and 0.3 L/min. In order to evaluate the effect of the airflow injected to generate the bubbles, the liquid flow condition remained since it was similar to the previous case. The average 2D velocity vector profile of swirling bubbly flow was measured by the UVP. It is the mean value of 5000 instantaneous profiles. The average profile is the summation of all instantaneous profiles divided by the number of profiles. Figure 6 illustrates the measurement results. The brown and blue vectors represent the velocity vector of the bubbles and liquid obtained from the UVP, respectively. The velocity vector of both phases in each airflow rate could be obtained separately. The bubble diameter in different airflow rates was maintained at an average of 3 mm, computed using the image processing technique on the picture obtained from a high-speed camera. The velocity vector of both phases obtained from the three cases exhibited the same level and similar trends, even the alteration in airflow rate.

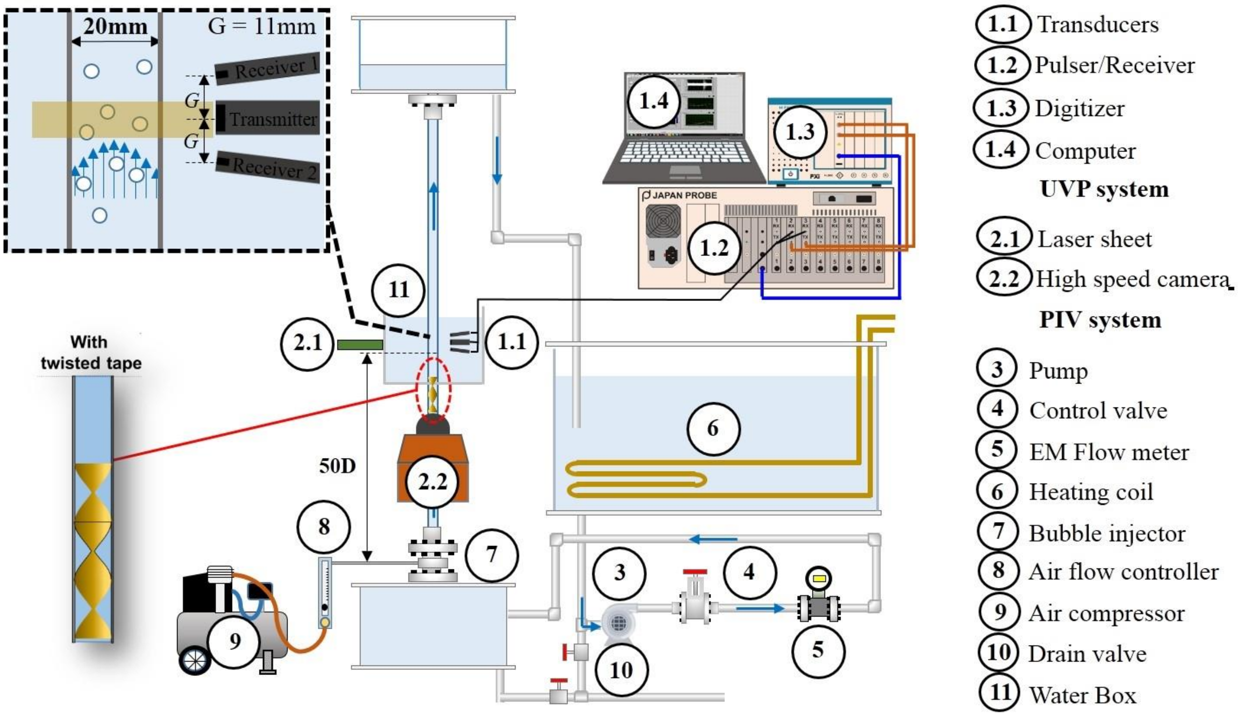


Fig. 4 - Schematic of the experimental apparatus and measurement system for swirling bubbly flow

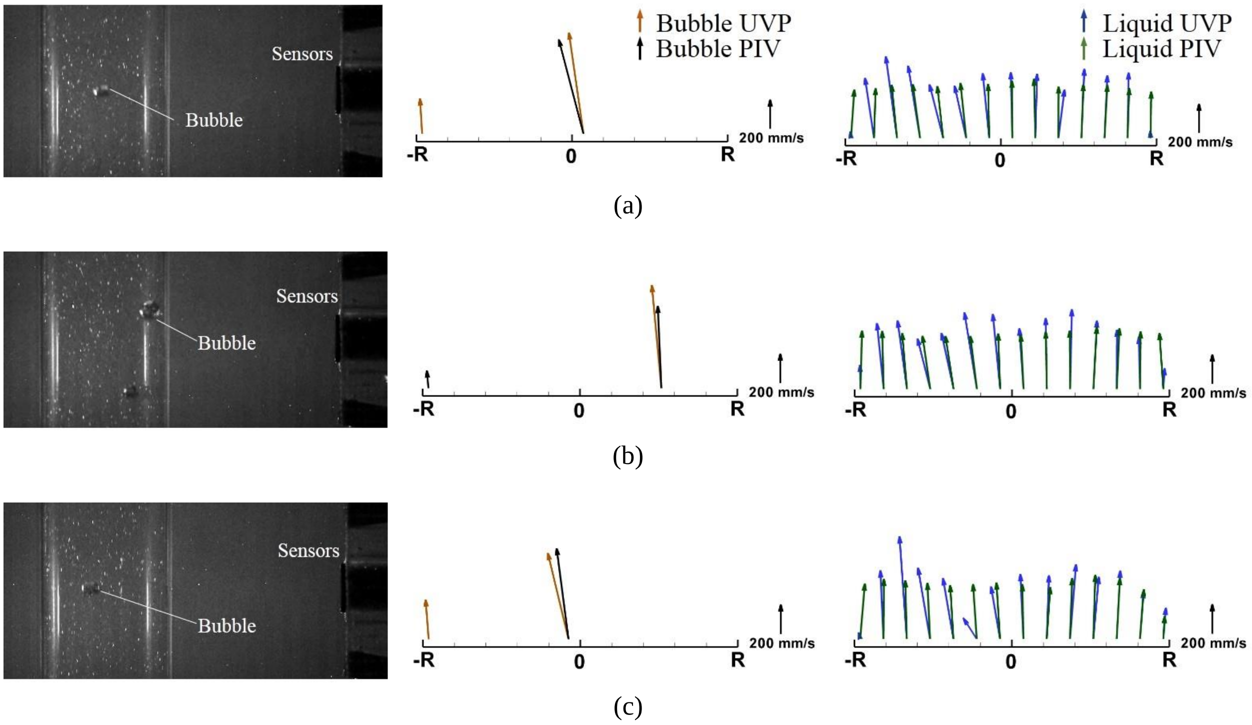
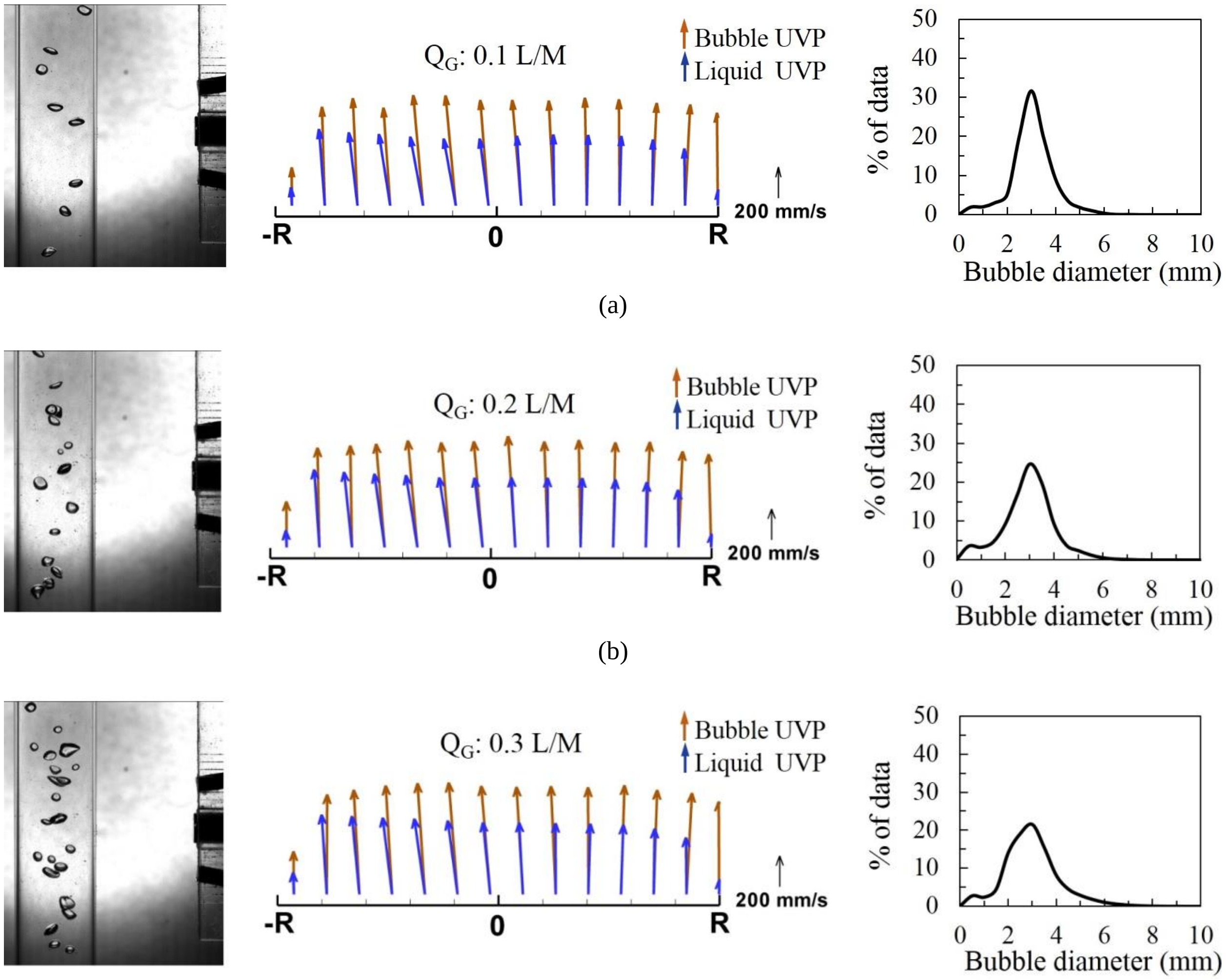


Fig. 5 - Measurement results of the instantaneous 2D velocity vector (swirling bubbly flow) at a low void fraction, and compared with the PIV (a) 1st measurement; (b) 2nd measurement, and; (c) 3rd measurement



(a)

(b)

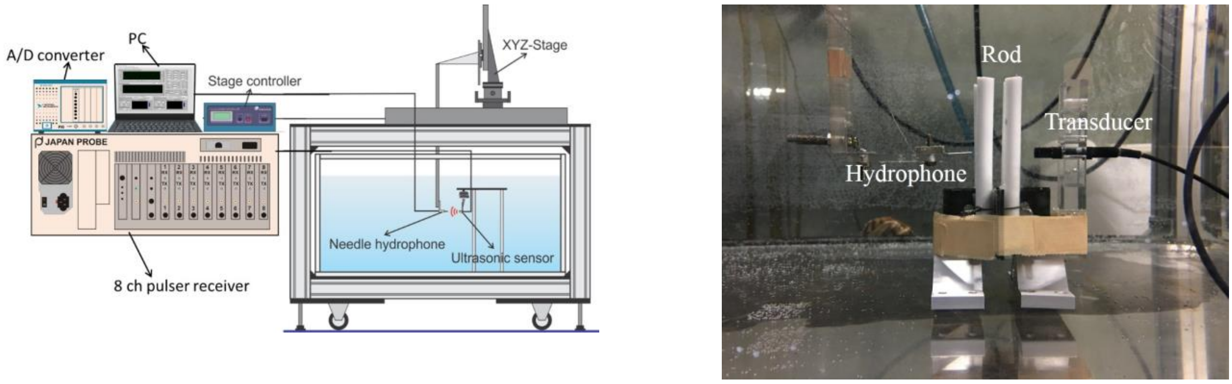
Fig. 6 - Measurement results of the instantaneous 2D velocity vector (swirling bubbly flow) at low void fraction, and compared with the PIV (a) 1st measurement; (b) 2nd measurement, and; (c) 3rd measurement

4. Sound Pressure Measurement on the Flow Channel Among Rod Bundles

The sound field emitted by the transducer distributed to the flow channel among rod bundles has to exist on the flow field where the velocity profile is to be collected. In order to confirm the distribution behavior of the sound field through the narrow channel in the rod bundle, sound pressure measurement is required. Figure 7 shows the experimental apparatus and measurement system. Water was employed for this experimental test. The transducer emitted the ultrasonic wave to the liquid by energizing the pulser/receiver. The needle hydrophone was mounted at the XYZ stage controller to derive the ultrasonic wave, and its signal port connected to the A/D converter and transferred the sound data in digital form to the PC, respectively. The needle hydrophone moved automatically, controlling the stage controller, and the sound pressure measurement can be executed in a particular grid and positioned two-dimensionally. In the experiment, the water temperature was controlled at ≈ 12.0 ±2°C, the axial distance x 120 mm, the half lateral distance y 20 mm, and the axial Δx and lateral Δy resolution defined as 1 mm and 0.5 mm, respectively. The ultrasonic signal transmitted by the transducer was recorded by a needle hydrophone to measure the sound intensity (I). It is a peak-to-peak voltage. The data were then converted to achieve the sound pressure level (SPL) using the following equation:

$$SPL = 20\log_{10}\frac{I}{I_{\max}} \qquad (7)$$

The sound pressure measurement was performed in three cases: without rods, with one pair of rods, and two pairs of rods installed. In the case without the rod, the hydrophone measures the sound intensity from the transducer surface to a depth of 120 mm. For the one pair of rods installed with a gap distance of 8 mm, the sound pressure was measured behind the rods and at a depth of 120 mm. Another pair of rods was then installed behind the previous rods, with the gap between the two pairs set at 8 mm. Figure 8 illustrates the sound pressure results. As the rods are not installed, good directivity and narrow beamwidth (< 8mm) on the sound field can be observed. The beam width determined during the period had an intensity higher than -6 dB. As the one pair and two pairs of rods were immersed, respectively, the sound field behind the installed rods had similarities to the result derived without rods. Therefore, it can be concluded that the sound beam emitted by the transducer is able to penetrate the narrow channel in the rod bundle configuration.



(a) (b)

Fig. 7 - Apparatus for sound pressure measurement (a) schematic experiment apparatus

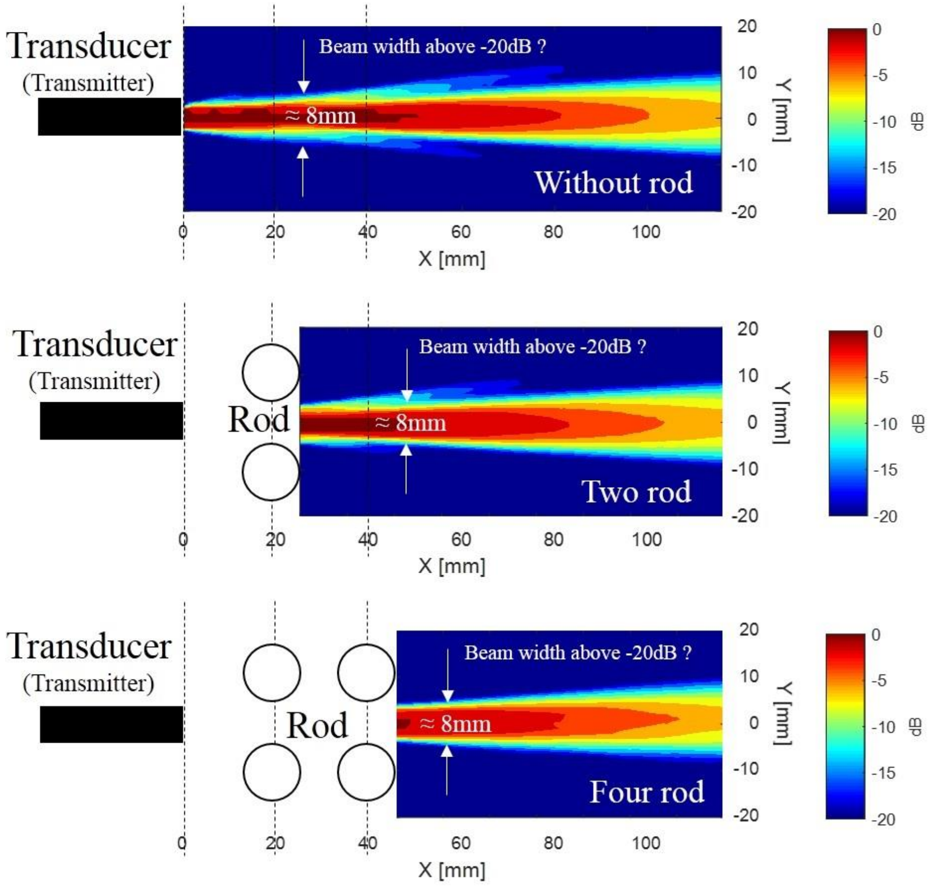


Fig. 8 - Sound pressure measurement results

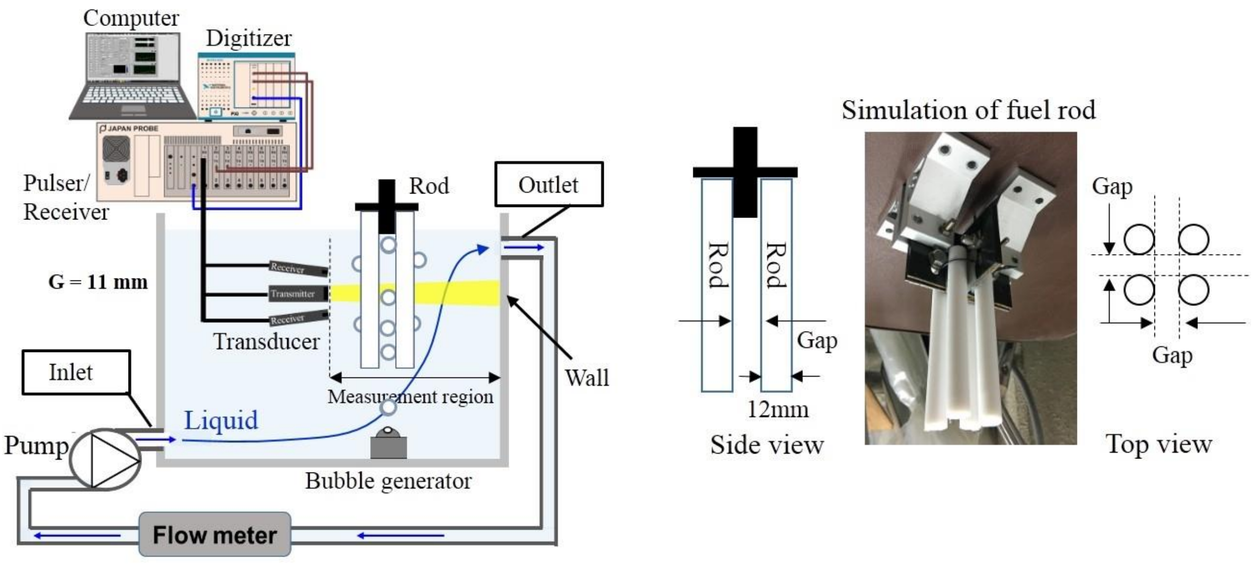
5. Experimental Measurement in the Rod Bundle

5.1 Experimental Setup

To achieve the main objective of the research, demonstration of the proposed UVP to investigate the 2D velocity vector of bubbly flow in rod bundles is required. The experiment was conducted in a rectangular column with four rods used to simulate the fuel rod bundle, as shown in Figure 9. The rod had a diameter of 12 mm. The gap between the two rods was set at ≈ 8 and 3 mm, respectively. Tap water was used as the working fluid, dispersed by nylon particles with a diameter of 80 μm and bubbles generated by the bubble generator. The water was circulated from the inlet to the outlet by the pump, forming the 2D flow field, while the impeller flow meter monitored the flow rate. The transducer system was immersed in the water and installed at position H = 20 mm from the outlet center. The measurement equipment and parameter settings were similar to the previous experiment.

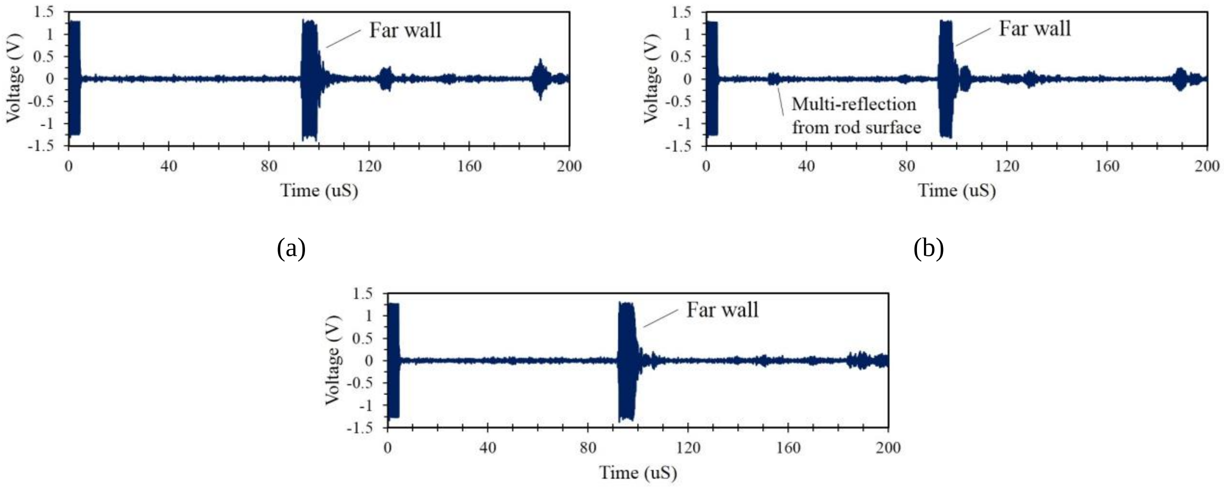
5.2 Echo Signal Testing

To verify the ability of the application in the rod bundle, the echo signal reflected from the reflector (whether bubble or liquid tracer in the flow field throughout the flow path in the small gap of the rod bundles), must be investigated to confirm the applicable gap length. The rod bundle configuration for testing was set as follows: without rods, rods installed with a 3 mm, and 8 mm gaps, respectively. Firstly, the testing was executed in the water flow, as shown in Figure 10. In the case where no rods were installed, the echo signal obtained was reflected by the reflectors in the flow field and the far wall without any multi-reflection. Then, as the rods were inserted in the flow field with a 3 mm gap, the multi-reflection of the echo signal was affected by the surface of the rod. Besides, the rod bundle gap was expanded to 8 mm, and the echo signal derived without the multi-reflection. The signal pattern was similar to the echo signal in the case without rods. Secondly, the echo signal obtained in the bubbly flow was evaluated, as illustrated in Figure 11. The echo signal was obtained without multi-reflection since no rods had been installed. When the rods were installed in the bubbly flow with a 3 mm gap, the huge, non-stationary reflective signal of the bubble was observed. However, the stationary reflection obviously occurred at the time of 30 μS, when the surface of the rod affected the multi-reflection. When the rod bundle gap was expanded to 8 mm, the stationary reflection, apart from that of the far wall, bubble, and liquid tracer, disappeared from the time domain echo signal, which means that multi-reflection did not occur on the signal. Therefore, the proposed UVP is applicable for use at a measurement gap of 8 mm, meeting the requirement for experimental investigation in [22].



(a) (b)

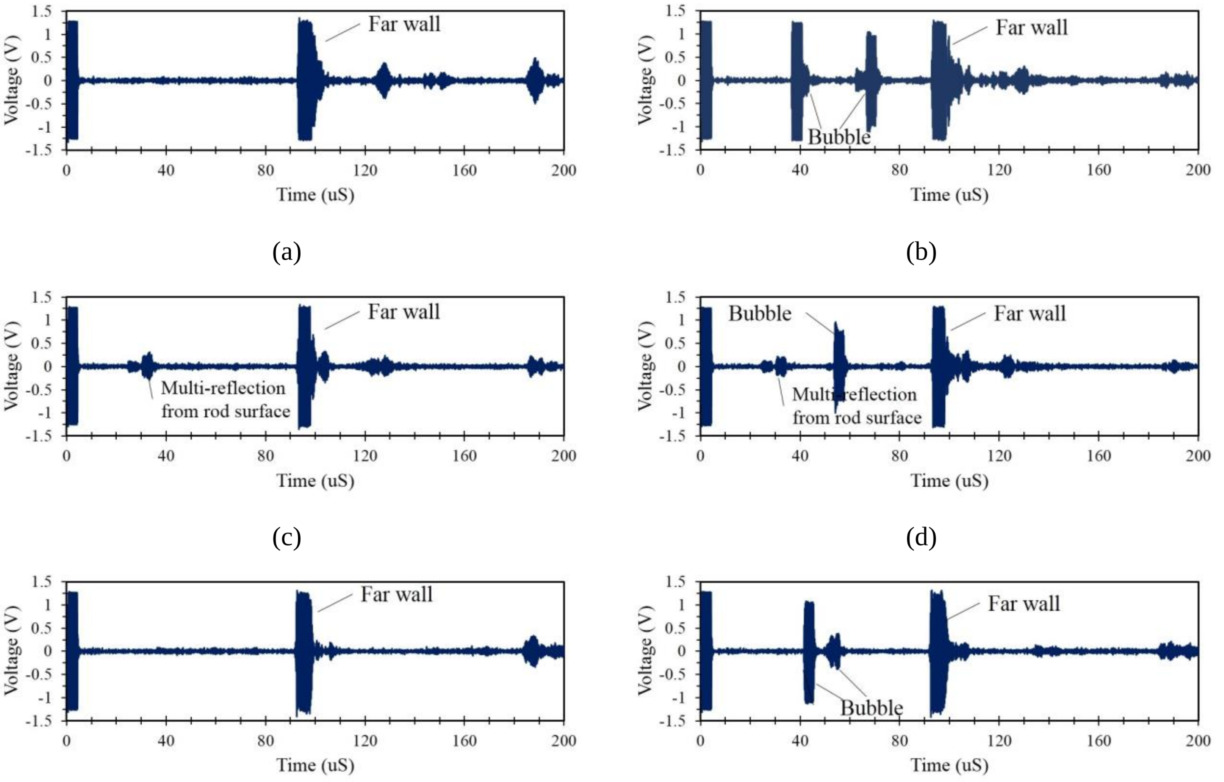
Fig. 9 - Schematic of the experimental apparatus and measurement system for rod bundles



(a) (b)

(c)

Fig. 10 - Echo signal in the water flow (a) without rod; (b) rods with a gap of 3 mm; (c) rods with a gap of 8 mm



(a) (b)

(c) (d)

(e) (f)

Fig. 11 - Echo signal in the bubbly flow (a) without rod and no bubbles; (b) without rod and with bubbles; (c) rod gap of 3 mm with no bubbles; (d) rod gap of 3 mm with bubbles; (e) rod gap of 8 mm with no bubbles, and; (f) rod gap of 8 mm with bubbles

5.3 Measurement Results of the Velocity Vector in Bubbly Flow

Figure 12 represents the measurement results of a 2D velocity profile derived from the bubbly flow distributed in the rod bundles. The profile represents the average value of 5000 instantaneous profiles. The 2D velocity profile of bubbles and liquid on the path between two pairs of rods can be reconstructed. The 2D velocity vector profile was obtained after the nearest field to the tank wall surface. The profile of the bubble phase was rising in a vertical direction, but only on the right side, with the vector pointing toward the outlet. The profile of the liquid phase at a distance between 30 mm, and 70 mm pointed in the direction of the outlet, indicating the reasonableness of the results obtained.

It can be concluded that the proposed UVP system is applicable for measuring the 2D velocity vector profile of bubbly flow in rod bundles.

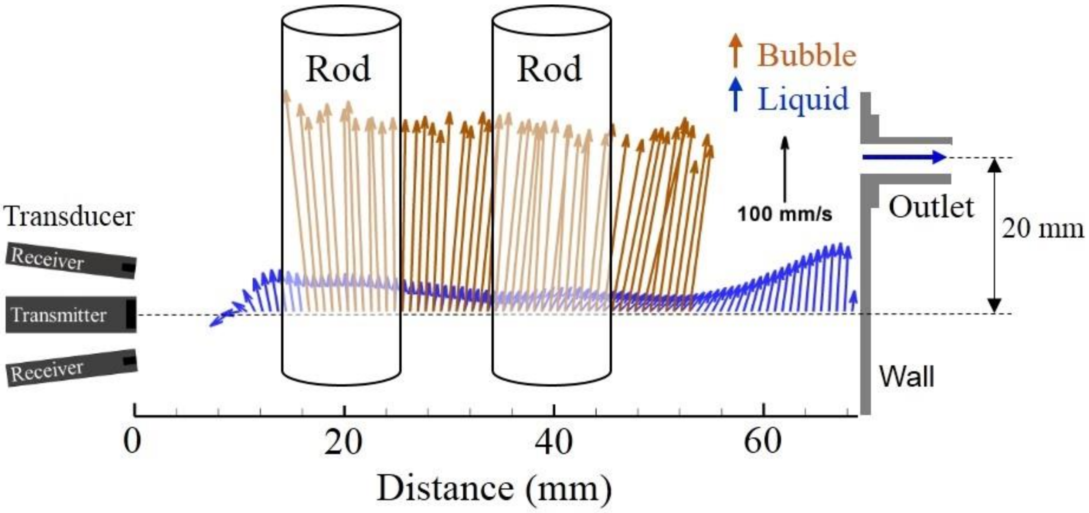


Fig. 12 - 2D velocity vector profile in a rod bundle

6. Conclusion

The UVP measurement, modified by the integration of the SUTS technique and multi-ultrasonic element sensor system, was proposed to measure the velocity vector of the bubbly flow in the narrow area of rod bundles. The preliminary applicability of this system was demonstrated by an experiment on swirling bubbly flow. The 2D velocity vector profile of the bubbles and liquid was obtained experimentally, and the sound pressure distribution in the narrow channel of the rod bundle then investigated to ensure the emitted ultrasonic wave could perform throughout a small channel. The echo signal reflected from the reflectors, bubble, and tracer particles in the small channel of the rod bundle, was also analyzed, indicating that the proposed UVP could be used in this application with a low level of multi-reflection. Lastly, the UVP system was applied to measure the 2D velocity vector profile in the narrow flow channel within the rod bundle configuration. The 2D velocity vector of bubbles and liquid was able to be reasonably derived. The effectiveness of the proposed UVP was found to be applicable for utilization in the experimental investigation.

References

[1] Julia, J., Hibiki, T., Ishii, M., Yun, B-J., & Park, G-C, (2009). Drift-flux model in a sub-channel of rod bundle geometry. International Journal of Heat and Mass Transfer, 163, 3032–3241.

[2] Lahey, R. T., & Moody, F. J., (1993). The thermal hydraulics of a boiling water nuclear reactor. American Nuclear Society Publishing.

[3] Yoo, J., Estrada, C. E., Yassin, P., & Hassan, A., (2016). Experimental Study on Bubble Dynamics and Wall Heat Transfer Arising from a Single Nucleation Site at Subcooled Flow Boiling Conditions. International Journal of Multiphase Flow, 84, 292-314.

[4] Anglart, H., (2002). Modelling of the Multi-Dimensional Phase Distribution in a BWR Fuel Assembly, Technical Meeting on Use of CFD Codes for Safety Analysis of Reactor Systems, Including Containment Modelling of Phase Distribution. Pisa, Italy.

[5] Muñoz-Cobo, J. L., & Chiva, S., (2017). Development of Conductivity Sensors for Multi-Phase Flow Local Measurements at the Polytechnic University of Valencia (UPV) and University Jaume I of Castellon (UJI). Sensors, 17, 1077.

[6] Seeger, A., Affeld, K., Goubergrits, L., Kertzscher, U., & Wellnhofer, E., (2001). X-ray-based assessment of the three-dimensional velocity of the liquid phase in a bubble column. Experiment in Fluids, 31, 193-201.

[7] Lindken, R., & Merzkirch, W., (2000). Velocity Measurements of Liquid and Gaseous Phase for a System of Bubbles Rising in water. Experiment in Fluids, 29, 194-201.

[8] Takeda, Y., (1986). Velocity Profile Measurement by Ultrasonic Doppler shift method. International Journal of Heat Fluid, 7, 313-318.

[9] Takeda, Y., (1991). Development of an Ultrasound Velocity Profile Monitor. Nuclear Engineering and Design, 126, 277-284.

[10] Kikuchi, K., Takeda, Y., Obayashi, H., Tezuka, M., & Sato, H., (2006). Measurement of LBE Flow Velocity Profile by UDVP. Journal of Nuclear Material, 356, 273-279.

[11] Kikura, H., Takeda, Y., & Durst, F., (1999). Velocity Profile Measurement of the Taylor Vortex Flow of a Magnetic Fluid using the Ultrasonic Doppler Method. Experiment in Fluids, 26, 208-214.

[12] Eckert, S., & Gerbeth, G., (2002). Velocity Measurements in Liquid Sodium by Means of Ultrasound Doppler velocimetry. Experiment in Fluids, 32, 542-546.

[13] Moriya, T., Kikura, H., & Takahashi, H., (2021). Basic Study on Ultrasonic Remote Leakage Position Estimation Method for Underwater Exploration. The 13th International Symposium on Ultrasonic Doppler Methods for Fluid Mechanics and Fluid Engineering. Zürich, Switzerland.

[14] Hitomi, J., Nomura, S., Murai, Y., De Cesare, G., Tasaka, Y., Takeda, Y., Park, H. J., & Sakaguchi H, (2021). Measurement of the inner structure of turbidity currents by ultrasound velocity profiling. International Journal of Multiphase Flow, 136, 103540.

[15] Yoshida, T., Tasaka, Y., Park, H. J., Murai, Y., Teramura, H., & Koseki, S., (2018). Inner structure visualization of fresh fruits utilizing ultrasonic velocity profiler. Journal of Visualization, 21, 253–265.

[16] Huther, D., & Lemmin, U., (1998). A constant-beam-width transducer for 3D acoustic Doppler profile measurements in open-channel flows. Measurement Science and Technology, 9, 1706-1714.

[17] Obayashi, H., Tasaka, Y., Kon, S., & Takeda, Y., (2008) Velocity vector profile measurement using multiple ultrasonic transducers. Flow Measurement and Instrumentation 19, 189–195.

[18] Aritomi, M., Zhou, S., Nakajima, M., Takeda, Y., Mori, M., & Yoshioka, Y., (2012). Measurement System of Two-phase Bubbly Flow using Ultrasonic Velocity Profile Monitor and Video Data Processing Unit. Journal of Nuclear Science and Technology, 33, 915-923.

[19] Murakawa. H., Kikura, H., & Aritomi, M., (2008). Application of Ultrasonic Multi-wave Method for Two-phase Bubbly and Slug Flow. Flow Measurement and Instrumentation, 19, 205-213.

[20] Wongsaroj, W., Hamdani, A., Thong-un, N., Takahashi, H., & Kikura, H., (2018). Extended Short-Time Fourier Transform for Ultrasonic Velocity Profiler on Two-Phase Bubbly Flow Using a Single Resonant Frequency. Applied Sciences, 9, 50.

[21] Wongsaroj, W., Owen, J. T., Thong-un, N., Takahashi, H., & Kikura, H., (2020). 2D velocity vector profile measurement on bubbly flow using ultrasonic technique. Mechanical Engineering Journal, 7, 19-00519.

[22] Yun, B., Park, G. C., Julia, J. E., & Hibiki, T., (2008). Flow Structure of Subcooled Boiling Water Flow in a Subchannel of 3x3 Rod Bundles. Journal of Nuclear Science and Technology, 45, 402–422.