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The development of ultrasonic velocity profiler for velocity vector measurement in bubbly flow

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In Boiling Water Reactors (BWRs), the multi-dimensional velocity distribution of the coolant in the bubbly flow region on fuel rod bundles of the reactor core is important to be elucidated by experimental investigation. The applicable measurement technique is required. To achieve this aim, this paper presents the development of an ultrasonic velocity profiler (UVP). The integration of special ultrasonic transducers and developed UVP signal processing is proposed to obtain a velocity vector of the bubbles and liquid in the bubbly flow. Firstly, the applicability of the proposed UVP was verified by the experiment in a swirling bubbly flow. The velocity vector profile measurement in bubbly flow was performed experimentally. The ability of the measurement was confirmed by comparing it with another technique. Lastly, the UVP system was applied to measure the velocity vector in the narrow flow channel in the rod bundle configuration.

Keywords: Ultrasonic, Velocity, Vector, Bubbly flow

1. Introduction

The Boiling Water Reactor (BWR) is a nuclear power plant having many operating units currently. The safety concept is the main issue for the reactor operation. The gas-liquid two-phase bubbly flow, which works as the coolant occurs in the reactor, significantly influences the safety aspect in BWR. In the reactor core, the spacer grids, which support the fuel rod bundle, are also as an effective mixing device by attaching flow deflectors such as swirling vanes. It is installed for heat transfer enhancement between fuel rod and coolant, which relates strongly to plant safety. The velocity distribution of the bubble and liquid, which has multi-dimensional motion, affects heat removal from the fuel to the coolant. Hence, the multi-dimensional velocity or velocity vector of the bubble and liquid distributed in fuel rod bundle is needed to be investigated. The experimental investigation on this parameter in rod bundles is a necessity. The measurement technique is needed.

Several intrusive techniques have been utilized to measure the velocity data in a two-phase bubbly flow, such as the conductive probe [1]. It 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 that can derive the velocity data of both phases have been proposed, such as Particle Image Velocimetry (PIV) [2]. It is capable of obtaining a velocity profile in two-dimensional (2D). The PIV requires optical access for the laser sheet and the camera to derive the 2D velocity profile at the region of interest, whereas the flow field in a typical fuel rod bundle with spacer-grids is optically obstructed by the rods themselves. The method cannot provide information on the full velocity profile or flow field along the flow path of rod bundles. Therefore, the measurement technique for obtaining a multi-dimensional velocity profile in this application is needed.

Ultrasonic Velocity Profiler (UVP) is a powerful method for visualizing the spatial-temporal velocity distribution in liquid flows [3]. 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.

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. Doppler signal influenced by the velocity of moving particle can be demodulated from the echo signals. The Doppler frequency f_D(i) directly relates to the velocity of the particle (i is position or channel). Hence, the velocity of the particle at that 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. [4] developed a three-dimensional velocity measurement in open-channel flow using one transmitter and four receivers, while Obayashi et al. [5] 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 can only measure in liquid flow.

In bubbly flow, Wongsaroj et al. [6] developed the UVP method to measure a 2D velocity vector profile in open-channel flow using one transmitter and two receivers. Nevertheless, this purpose has not yet been applied in the small channel which has a narrow flow field like in the rod bundles. This paper presents the development of the UVP system to obtain the multi-dimensional velocity distribution or velocity vector of the bubbly flow in the narrow area which is applicable for experimental investigation in the rod bundle application. This study focus on two-dimensional measurement.

2. UVP measurement in bubbly flow

2.1 Single Ultrasonic gas-liquid Two-phase Separation (SUTS)

To separate the gas bubble and liquid velocity data, the phase separation algorithm is necessary. Fig. 1 illustrates the schematic of the Single Ultrasonic gas-liquid Two-phase Separation (SUTS), which is a phase separation technique. It is contained in the UVP system to separate the velocity data of both phases.

This technique is the integration of time-frequency analysis and Doppler amplitude classification [6]. Short-Time Fourier Transform (STFT) is selected to be a time-frequency estimator. It decomposes frequency components of the Doppler signal according to the time. The frequency value can be observed from peak energy occurring on spectrogram in each time location as express in equation (2) and (3).

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

$$P(k, f_D) = |X(k, f_D)|^2 \quad (3)$$

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 time-frequency function. Then, each frequency component is classified as Doppler frequency of particle and bubble by comparing the value of Doppler amplitude in that time location with a 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 bubble and liquid groups is averaged separately. Then, the velocity value of bubble and liquid can be obtained separately by placing these Doppler frequencies into equation (1).

$$V_x(i) = \frac{c}{2f_0 \sin\theta\,(i)}\left(f_{D1}(i) - f_{D2}(i)\right) \quad (4)$$

$$V_y(i) = \frac{c}{2f_0\,(1 + \cos\theta\,(i))}\left(f_{D1}(i) - f_{D2}(i)\right) \quad (5)$$

$$V(i) = \sqrt{V_x^2(i) + V_y^2(i)} \quad (6)$$

2.2 Integration of SUTS and multiple transducers for two-dimensional measurement in bubbly flow

To obtain a 2D velocity vector profile, the multiple transducers with one transmitter and two receivers are utilized, as shown in Fig. 2, which is called 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 of receivers 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 equation (4) to (6).

To achieve the measurement in bubbly flow, the SUTS is integrated with a multi-ultrasonic element sensor system and applied into the UVP which is called 2D vector UVP gas-liquid separation system. It can measure the 2D velocity vector profile of bubble and liquid in the bubbly flow. Fig. 3 represents a system schematic of the integrated measurement system. The sensor system is connected to the multiple-channel pulser/receiver. The echo signals were obtained via receivers 1 and 2. The signals are amplified by pulser/receiver. The signals are sent to UVP processing, including the SUTS to compute the velocity of bubble and liquid (particle); $V_{\text{particle1}}$,

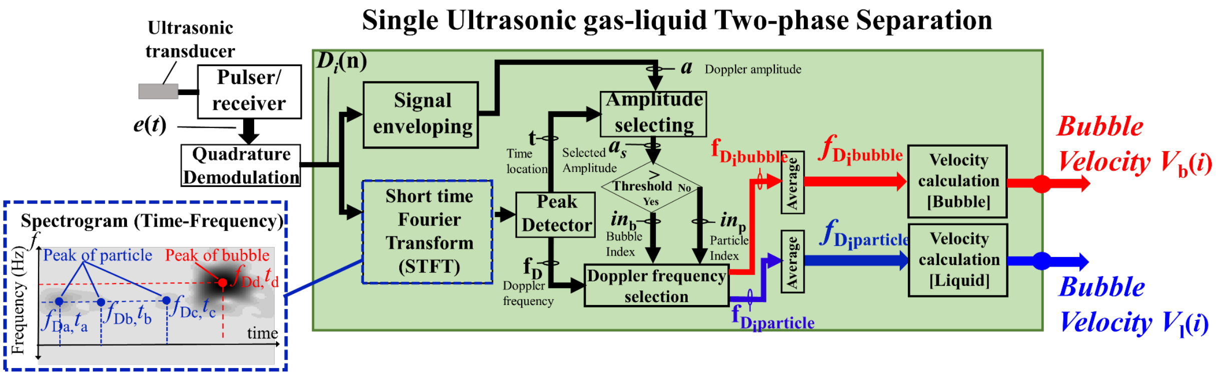

Figure 1: the schematic of the UVP with SUTS

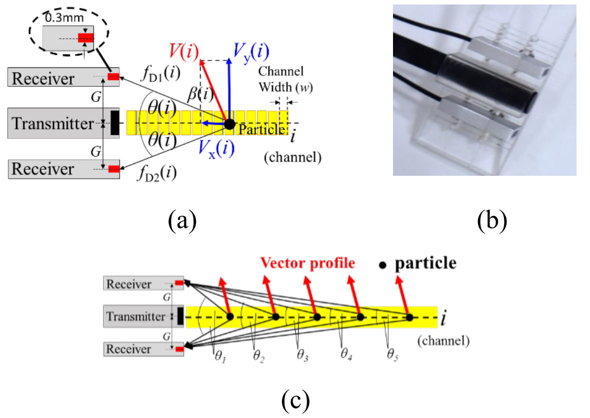

Figure 2: multi-ultrasonic element sensor system, (a) schematic of measurement with a single particle, (b) image of transducer, (c) schematic of measurement with multiple particles,

$V_{bubble1}$, $V_{particle2}$, and $V_{bubble2}$. The 2D velocity of bubble and liquid can then be reconstructed separately by the vector reconstruction section based on the equation (4) to (6).

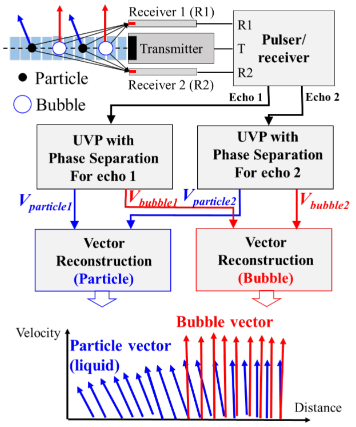

Figure 3: the schematic of the integration of UVP with SUTS and multi-ultrasonic element sensor system

3. Two-dimensional measurement in the swirling bubbly flow

In order to demonstrate the performance of the UVP, firstly, the experimental measurement was executed in the swirling bubbly flow. Fig. 4 represents a schematic diagram of the experimental apparatus and the UVP system. The UVP system consisted of a multi-ultrasonic element sensor system; one 4MHz transmitter and two 4MHz receivers, a multiple channels ultrasonic pulser/receiver, a digitizer, and a computer with LabVIEW software version 2011. The pulser/receiver emitted ultrasonic pulses via the transmitter and received the echo signals through receiver1 and receiver2. Then, the echo signals were received and amplified by the pulser/receiver. The signals were converted to a digital signal by the digitizer, with a sampling rate of 250 MS/s. Signal data from the digitizer was sent to the computer via PCI port. The signal processing and velocity computation were performed using LabVIEW software. The transducers were installed in the test section (in the water box). The pipe was made from acrylic with an internal diameter of 20 mm. Tap water at temperature 12ºC ±2ºC dispersed with nylon particles 80 µm and bubbles were working fluid. The water was circulated from the bottom to the top by the pump. The electromagnetic flowmeter was used to measure the water flow rate. A bubble generator was put on upstream 50D from the test section to generate the bubble. The swirling motion was induced by a twisted tape inserted in the acrylic pipe. The twist ratio y was set to = 3 to be the same with industrial purpose. For the UVP parameter setting, the basic frequency was f_0 4MHz with the 4 cycles per pulse, the voltage was 160 Vp-p, pulse repetition frequency f_{PRF} was 4 kHz, and the number of repetitions N_{REP} 128.

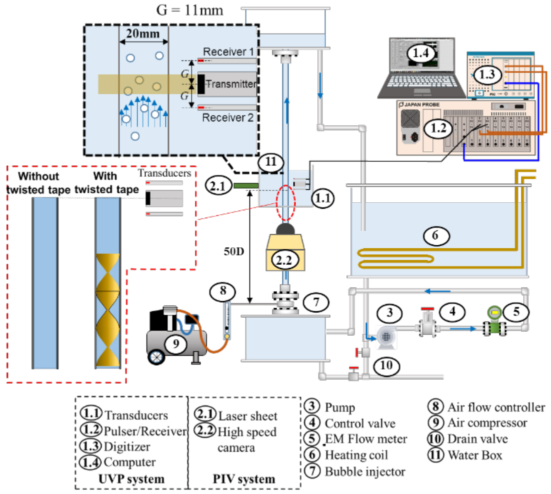

Figure 4: the schematic of the integration of UVP with SUTS and multi-ultrasonic element sensor system

In this experiment, the U_L was set at 500 mm/s, The average 2D velocity vector of swirling bubbly flow was measured by the UVP and the PIV. Fig. 5a illustrates the measurement results of the UVP. The brown color vector and the blue color vector represent the velocity vector of the bubble and liquid obtained from the UVP. The velocity vector of both phases could be obtained separately. Fig. 5b and Fig. 5c show the comparison of the velocity vector measurement with the PIV measurement; bubble and liquid, respectively. The discrepancy of comparison was almost 15%, as shown in Fig. 6. However, the bubble has a high response toward the light, the bubble outside the laser plane that moves in a not similar direction to the bubble in the plane is able to be captured and appeared on the PIV image which causes the deviation in the measurement result of tangential velocity and direction of the bubble velocity vector.

4. Measurement in the rod bundle

To achieve the target, the demonstration of 2D vector UVP gas-liquid separation system to investigate the 2D velocity vector of bubbly flow in rod bundles is required. The experiment was conducted in the rectangular column in which four rods were used to simulate to be the fuel rod bundle, as shown in Fig. 7. The rod diameter was 12 mm

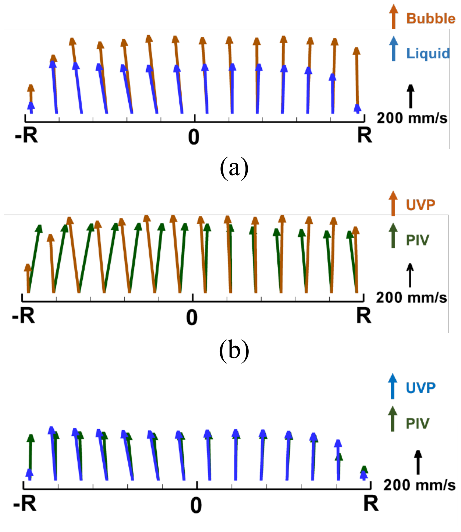

Figure 5: Measurement result in swirling bubbly flow, (a) the result of the UVP, (b) the comparison result of bubble, (c) the comparison result of liquid

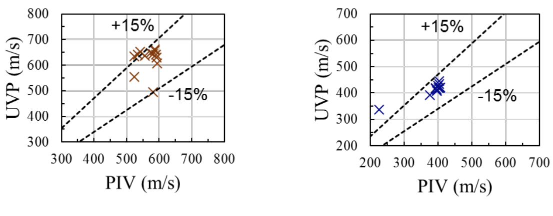

Figure 6: Discrepancy of measurement in swirling bubbly flow, (a) bubble, (b) liquid

The gap between the two rods was set at ≈ 8 mm. This configuration was referred as the experimental investigation proposed by [7]. The working fluid was tap water dispersed by nylon particle with a diameter of 80 µm and bubble generated by the bubble generator. The water was circulated from the inlet to the outlet by the pump. The 2D flow field was formed. The impeller flow meter monitored the flow rate. The transducer was immersed in the water and installed at position H = 20 mm from the outlet center. The measurement equipment and parameter setting were similar to the previous experiment.

Fig. 8 represents the measurement result of a 2D velocity profile derived from the bubbly flow distributed in the rod bundles. The profile was the average value of 5000 instantaneous profiles. The 2D velocity profile of bubble and liquid on the path between two pairs of rods can be reconstructed. The 2D velocity vector profile after the near field region to the tank wall surface was obtained. The profile of the bubble phase had a vertical rising direction, only on the right side of the profile the vector direction pointed to the outlet. The profile of the liquid phase at a distance between 30 mm and 70 mm has a direction to the outlet, indicating the reasonableness of the result obtained. It can be concluded that 2D vector UVP gas-liquid separation system is applicable to measure the 2D velocity vector profile of the bubbly flow in the rod bundles application.

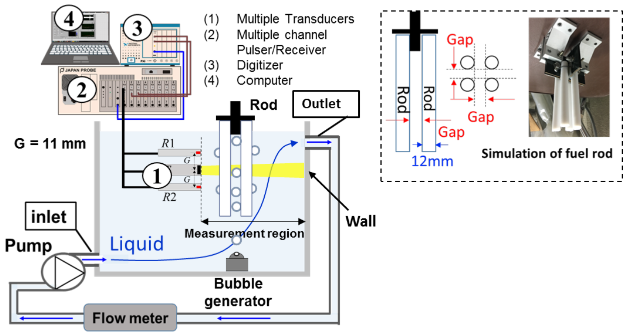

Figure 7: Experimental setup for the UVP measurement in rod bundle

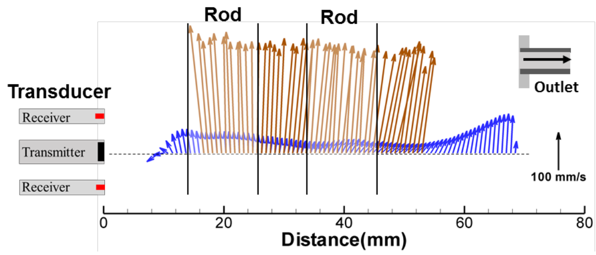

Figure 8: 2D velocity vector profile in rod bundle

5. Summary

The UVP measurement which has modified by the integration of Single Ultrasonic gas-liquid Two-phase Separation (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. Preliminary, the applicability of this system was verified by the experiment on a swirling bubbly flow. The 2D velocity vector profile in bubbly flow was obtained experimentally. Lastly, the UVP system was applied to measure the 2D velocity vector profile in the narrow flow channel in the rod bundle configuration. The 2D velocity vector of bubble and liquid can be derived reasonably.

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