DOI: 10.15669/pnst.7.103

Progress in Nuclear Science and Technology
Volume 7 (2025) pp. 103-109

ARTICLE

Development of a gas flowrate measurement system in gas–liquid two-phase flow using pulsed ultrasound

Naruki Shoji [a*], Hideharu Takahashi [b], Hiroshige Kikura [b], Koji Teramoto [a] and Hideki Kawai [a]

[a] *College of Design and Manufacturing Technology, Robotics and Mechanical Engineering Research Unit, Muroran Institute of Technology, 27-1 Mizumoto, Muroran, Hokkaido 050-8585, Japan;* [b] *Institute of Science Tokyo, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8550, Japan*

Gas–liquid two-phase flow is a fundamental fluid phenomenon frequently seen in industrial flows. Understanding the behavior of two-phase flow and monitoring its flow conditions is important for maintaining efficiency and safety in fluid machine control. The performance of gas-lift pumps, which use gas–liquid two-phase flow, depends on the two-phase flowrate and pattern in the pipe. Therefore, a noninvasive monitoring method of the two-phase flow in the pipe is necessary. This study focused on ultrasonic measurement techniques for noninvasive measurement of conditions inside a pipe and developed a measurement system to measure gas-phase flowrate in gas–liquid two-phase flow using pulsed ultrasound. A simultaneous measurement system of gas-phase void fraction and flow velocity distribution was developed by combining the pulse-echo and pulsed Doppler methods using the opposed transducer pair. Furthermore, the gas-phase flowrate was computed by integrating the void fraction and velocity distribution concerning the pipe cross-section. An air–water two-phase flow was generated in a pipe with a 50-mm inner diameter to verify the accuracy of the gas flowrate measurement using this measurement system. The air flowrate was varied, and the flowrate was measured at each flowrate condition using this system. The results revealed that the system measured the gas flowrate in two-phase flow with a relative error within ±15%.

Keywords: ***ultrasound; two-phase flow; flowrate; signal processing; non-inversive; pulse-echo method; pulsed doppler method***

Nomenclature

A	amplitude of echo signal	c	sound velocity
D_b	bubble length	f_{PRF}	pulse repetition frequency
N_{rep}	number of pulse repetition	Q	volumetric flowrate
v_b	bubble rising velocity	x	measurement position
z	complex Doppler signal	α	void fraction
ρ	density	τ	arrival time of echo signal

1. Introduction

Methane hydrate has been recently attracting attention as a new energy resource for carbon neutrality. Methane hydrate is stored on the seafloor at low temperatures and high pressures. The use of gas-lift pumps [1] has been considered for transporting the drilled material. A gas-lift pump is a method of generating an upward flow in a pipe by blowing gas into a pipe filled with liquid to lower the apparent specific gravity and is one of the fluid machinery that uses the gas–liquid two-phase flow phenomenon. However, the pumping performance of a gas-lift pump depends on the gas blowing flowrate, blowing position, etc. Additionally, morphological changes, such as the gasification of methane hydrate in the pipe, which changes the pumping performance, are possible in methane hydrate transportation. Therefore, gas flowrate changes due to phase changes in the pipe need monitoring to maximize the pumping efficiency. Generally, non-transparent pipes, such as metal pipes, are used for transport pipes. Additionally, methane hydrate, which is a solid, flows in the pipes. Hence, a noninvasive measurement method is required to monitor the gas flowrate in the non-transparent pipe. Therefore, the purpose of this study is development of a gas flowrate measurement method in multiphase flow using ultrasound.

Information on both the fraction of gas-phase in the pipe cross-section and the gas-phase velocity is required to measure the gas-phase flowrate in a pipe. The shape

*Corresponding author. E-mail: shoji@us.nr.titech.ac.jp

measurement of bubbles in a pipe cross-section using ultrasonic tomography has been studied conventionally as a gas-phase measurement in multiphase flow using ultrasound [2]. The ultrasonic tomography method can obtain information on the shape of bubbles but does not provide velocity information, which cannot be converted to flowrate. In contrast, Wongsaroj et al. [3] used an ultrasonic velocity profiling method, which is a reflector velocity measurement method using ultrasonic pulses [4], to bubbly flow and succeeded in measuring rising bubble velocity. However, this method only provides information on the movement velocity of the bubble interface and does not provide information on the gas-phase fraction in the pipe cross-section.

This study developed a system to simultaneously measure the gas-phase fraction and velocity, which is necessary for gas flowrate measurement in multiphase flow. The system was applied to a water–air two-phase flow in a vertical pipe with a known injected gas-phase flowrate to verify the validity of the system.

2. Simultaneous measurement of bubble position, size, and velocity distribution

2.1. Concept of volumetric gas volume flowrate measurement in gas–liquid two-phase flow

The volume flowrate in the pipe can be obtained by integrating the velocity distribution concerning the pipe cross-section in the case of single-phase flow [5]. Conversely, obtaining fractions for each phase is necessary for gas–liquid two-phase flow. The volume flowrate Q_i of phase i in the pipe can be obtained by the following equation, where the fraction of phase i at the position from the center of the pipe x, the circumferential angle of the pipe φ is $\alpha_i(\varphi, x)$ and the flow velocity is $v_i(\varphi, x)$.

$$Q_i = \int_0^{2\pi} \int_0^{\frac{D}{2}} \alpha_i(\phi, x) v_i(\phi, x) x dx d\phi \tag{1}$$

where D is the pipe's inner diameter. Eq. (1) can be simplified as follows, assuming that the fraction and velocity distribution are symmetrical in the circumferential direction of the pipe:

$$Q_i = 2\pi \int_0^{\frac{D}{2}} \alpha_i(x) v_i(x) x dx \tag{2}$$

where phase i is gas-phase and α means the void fraction. The void fraction and bubble velocity distribution in the pipe needs to be determined to measure the gas flowrate in gas–liquid two-phase flow, as shown in Eq. (2). This study measured the bubble position and size by the pulse-echo method to determine the void fraction distribution, and the bubble velocities were measured by the pulsed Doppler method.

2.2. Bubble position and size measurement

Ultrasonic wave reflection occurs at the interface between the propagating medium and the reflector (the boundary where the acoustic impedance change occurs). Acoustic impedance Z is a material-specific physical parameter that is calculated as $Z = \rho c$ (ρ: density, c: sound velocity). The reflectivity R between the interface is expressed by the following equation in the case of perpendicular incidence of ultrasonic waves from medium layer 1 to layer 2.

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \tag{3}$$

where Z_1 and Z_2 are the acoustic impedances of the medium layers 1 and 2, respectively. The ultrasonic pulse-echo method utilizes reflection from the interface of the two mediums to measure the position of the reflector. **Figure 1(a)** shows the principle of position measurement by the pulse-echo method. An ultrasonic pulse is transmitted from an ultrasonic transducer (TDX), and pulse reflection occurs at the reflector interface. The reflected signal is received by the same TDX and recorded as an echo signal. The reflector interface position d_R can be determined as follows:

$$d_R = \frac{c\tau_R}{2} \tag{4}$$

where τ_R is the echo arrival time from transmission time. Ultrasonic waves are almost totally reflected and do not penetrate the gas reflector due to the large difference in acoustic impedance between the liquid and gas when the propagation medium is liquid and the reflector is gas. For instance, the reflectivity R obtained from Eq. (3) is almost one if the liquid is water (density: 1000 kg/m^3, sound velocity: 1480 m/s) and the gas is air (density: 1.3 kg/m^3, sound velocity: 340 m/s). Therefore, ultrasonic waves do not penetrate inside the gas phase in gas–liquid two-phase flow, and only the position of the interface facing the TDX can be measured when only one TDX is used. This study used the reflector size estimation method using two TDXs to estimate the size of the gas phase flowing in a liquid and convert it to a void fraction. **Figure 1(b)** shows the schematic diagram of bubble size measurement using opposed transducer pair. Two TDXs (TDX1 and TDX2)

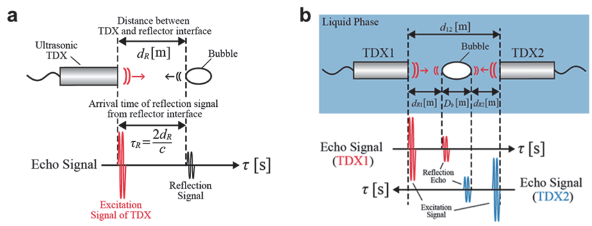

Figure 1. Schematic diagram of (a) bubble position measurement by pulse-echo method, (b) size measurement using opposed transducer pair.

are installed at a fixed distance d_{12} from each other at a common installation angle to share the measurement lines. Each TDX measures the distance to the phase interface from Eq. (4) when a bubble passes between the TDXs. The bubble length D_b in the propagation axis direction can be obtained by the following equation, where the distance between TDX1 and the reflector interface is d_{R1} and the distance between TDX2 and the reflector interface is d_{R2} [6].

$$\begin{aligned} D_b &= d_{12} - (d_{R1} + d_{R2}) \\ &= d_{12} - \frac{c_L(\tau_{R1} + \tau_{R2})}{2} \end{aligned} \tag{5}$$

where d_{12} is the distance interval between TDXs. The bubble size and position can be measured using the method combined with the pulse-echo method and opposed transducer pairs.

2.3. Bubble rising velocity measurement

This study used the pulsed Doppler method to measure the velocity of rising bubbles. **Figure 2(a)** shows the schematic diagram of the bubble rising velocity measurement by the pulsed Doppler method. Ultrasonic pulses are transmitted to the reflector at an angle θ in a direction orthogonal to the flow, and the reflected echo signal is received at the same TDX. The reflected echo signal contains a Doppler frequency shift proportional to the moving velocity of the bubbles, $f_c + f_D$, where the center frequency of the transmitted ultrasound is f_c. Therefore, the velocity of the bubbles can be obtained as follows by extracting the Doppler frequency component f_D:

$$v_b(x) = \frac{c f_D(x)}{2 f_c \sin\theta} \tag{6}$$

where x is the measurement position that can be obtained by Eq. (4). Extracting Doppler frequency components from echo signals has several methods [7]. This study used an autocorrelation method [8] that can calculate velocity with relatively few pulse repetitions. This method detects the phase shift of the echo signal accompanying the reflector movement and converts it to the Doppler frequency. **Figure 2(b)** illustrates the phase shift of the reflected echo signal in the time direction by the reflector movement. The quadrature demodulation is applied to the echo signal to detect the phase shift $\Delta\varphi$. The echo signal is represented as follows where the reflected echo signal

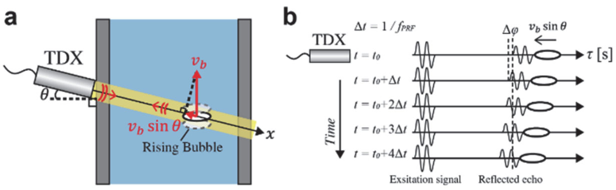

Figure 2. Schematic diagram of (a) bubble velocity measurement by pulsed Doppler method, (b) reflected echo signal.

at i-th pulse repetition is $s^{(i)}(\tau)$:

$$s^{(i)}(\tau) = A(\tau)\cos\{2\pi(f_c + f_D)\tau\} \tag{7}$$

where A is signal amplitude. A complex signal $z^{(i)}(\tau)$ containing only the Doppler frequency component is obtained by applying quadrature demodulation processing to Eq. (7).

$$\begin{aligned} &z^{(i)}(\tau) \\ &\quad = \mathrm{LPF}\left[s^{(i)}(\tau)\cos(2\pi f_c \tau)\right] \\ &\qquad + j\mathrm{LPF}\left[s^{(i)}(\tau)\sin(2\pi f_c \tau)\right] \\ &\quad = \frac{A(\tau)}{2} e^{-j2\pi f_D \tau} \end{aligned} \tag{8}$$

where LPF represents the low-pass filtering process for the signal in [ ], and j is the imaginary unit. Then, the Doppler frequency f_D is obtained by calculating the phase difference $\Delta\varphi$ in the pulse repetition direction (time direction) using the complex signal $z^{(i)}(\tau)$. The averaged phase difference is used in N_{rep}-times pulse repetition to improve the accuracy of the measurement velocity [9].

$$\begin{aligned} f_D &\approx \frac{\Delta\phi}{2\pi\Delta t} \\ &= \frac{f_{PRF}}{2\pi}\tan^{-1}\left(\frac{1}{N_{rep}}\sum_{i=1}^{N_{rep}-1} z^{(i)}(\tau)\bar{z}^{(i-1)}(\tau)\right) \end{aligned} \tag{9}$$

where superscript bars denote complex conjugates, and f_{PRF} is the pulse repetition frequency ($\Delta t = 1/f_{PRF}$). Finally, the bubble velocity at position x can be obtained by substituting the obtained Doppler frequency into Eq. (6).

2.4. Construction of a combined measurement system for bubble position, size, and velocity distribution measurement

The position and size of bubbles in gas–liquid two-phase flow were measured using two ultrasonic transducers based on the reflection time and amplitude of the ultrasonic echo signal, and the pulsed Doppler method provides the bubble rise velocity from the phase shift of the echo signal using a single ultrasonic transducer, as described in Sections 2.2 and 2.3. These two methods do not interfere with each other, and each processing method can be simultaneously applied. Thus, the measurement system was developed to realize combining these methods and simultaneously measure bubble position, size, and velocity. **Figure 3** illustrates the schematic diagram of the developed ultrasonic measurement system for gas–liquid two-phase flow measurement with the opposed transducer pair. The system broadly consists of an opposed transducer pair, ultrasonic measurement hardware, and a hardware control and signal processing computer. This study designed and implemented the measurement hardware. The hardware generates and controls

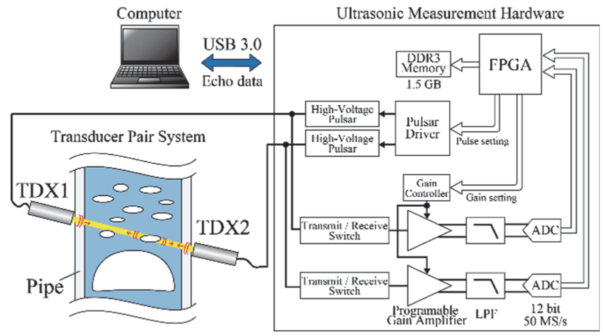

Figure 3. Schematic diagram of the developed ultrasonic measurement system.

the timing of transmission and reception of ultrasonic pulses in two transducers, and amplifies and filters the received signals. The received echo signals are sampled by the implemented analog-to-digital converters with a sampling speed of 50 MS/s and a voltage resolution of 12 bits. The signal processing methods described in Sections 2.2 and 2.3 are applied to the sampled echo signal to determine the bubble position, size, and velocity.

3. Experimental setup for gas volume flowrate measurement in gas–liquid two-phase flow

The system was applied to a air–water two-phase flow in a vertical pipe with a known injected gas-phase flowrate, and compared with the reference gas flowrate and measured value to verify the validity of the measurement system. **Figure 4(a)** shows the test facility to validate gas volume flowrate measurement with the developed system, **Table 1** shows the experimental conditions, and **Table 2** shows the measurement parameters. Water was raised in a vertical acrylic pipe with an inner diameter D of 50 mm, and compressed air was injected by a compressor at the air injection section installed at the bottom of the pipe. The water and air flowrates were monitored by an electromagnetic flow meter and a float flow meter, respectively. This experiment installed the ultrasonic transducer pair in a test section at 3 m from the air injection section (L/D = 60) to verify the feasibility of measuring the air flowrate in water–air two-phase flow using the developed ultrasonic measurement system. **Figure 4(b)** shows a water box around the test section pipe for acoustic matching to pass through ultrasonic waves into the pipe from outside the pipe. Each ultrasonic transducer was installed at a 13° angle. This angle was determined by considering the velocity limit that can be measured by the pulsed Doppler method. This experiment kept the water flowrate constant at 50 L/min and the air flowrate was varied between 0.5 and 4.5 L/min, and ultrasonic measurements were applied at each air flowrate.

4. Results and discussions

4.1. Bubble position, size, and velocity distribution measurement

Figure 5 presents the spatiotemporal intensity distribution of the echo signals received at TDX1 and TDX2. The white-

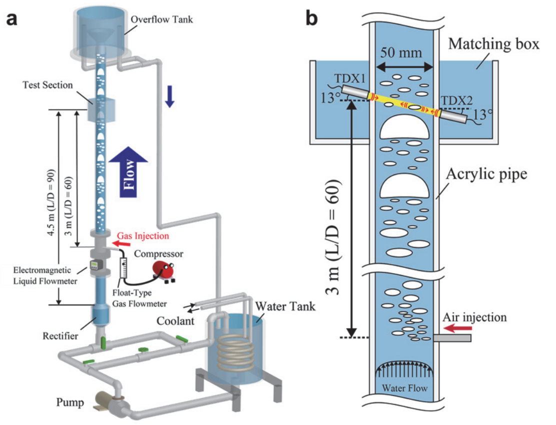

Figure 4. Schematic diagram of (a) test facility for gas–liquid two-phase flow, (b) measurement setup.

Table 1. Experimental conditions.

Parameter	Condition
Fluid	Air–water
Pipe diameter	50 mm
Water temperature	15°C
Water flowrate	50 L/min
Air flowrate	0.5, 1.6, 2.6, 3.5, and 4.5 L/min
Superficial liquid velocity	0.42 m/s
Superficial gas velocity	0.004–0.038 m/s

Table 2. Measurement conditions.

Parameter	Condition
Sound velocity in water	1466 m/s
Ultrasonic center frequency	4 MHz
Wavelength in water	0.37 mm
Ultrasonic element diameter	5 mm
Pulse repetition frequency	1500 Hz
Number of pulse repetitions per one velocity distribution	32

colored areas indicate high reflection intensity and represent reflections from the gas–liquid interface. Figures 5 (a) and (b) show the case of air flowrates of 0.5 and 4.5 L/min, respectively. The inside of the pipe was a bubbly flow with small bubbles continuously rising at the air flowrate of 0.5 L/min. Therefore, the continuous rise of small bubbles on the ultrasonic path was captured, as shown in Figure 5 (a). Conversely, the inside of the pipe has a slug flow with large bubbles and small bubbles alternately rising at the air flowrate of 4.5 L/min. The reflection signals with relatively long durations were obtained between 0–0.1 and 0.5–0.6 s, as shown in Figure 5 (b), while intensity distributions with dot patterns were obtained in other regions. The intensity distribution with long time durations is the reflection from the large bubble interface that

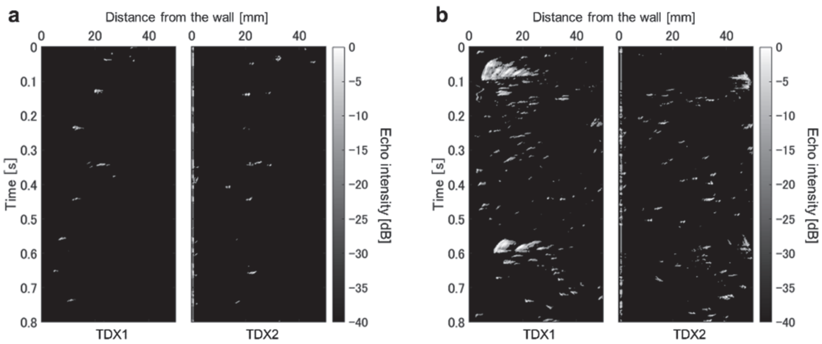

Figure 5. Spatiotemporal echo intensity distribution. Air flowrate: (a) 0.5 L/min, (b) 4.5 L/min.

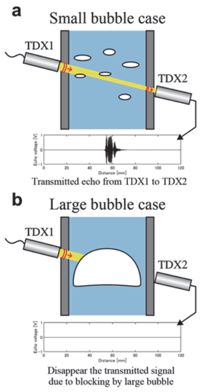

Figure 6. Transmitted signal from TDX1 to 2.

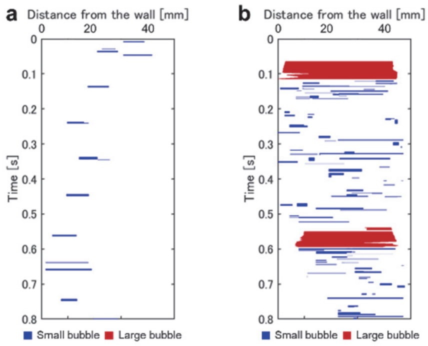

Figure 7. Reconstructed spatiotemporal bubble distribution Air flowrate: 0.5 L/min; Air flowrate: 4.5 L/min.

occupies the pipe cross-section, while the dot pattern is the reflection from the small bubble interface. Almost all of the transmitted ultrasonic pulses are reflected at the large bubble interface when passing through a large bubble, thus bubbles behind the large bubble interface are not detected. However, multiple intensity peaks were observed in the spatial direction in the reflection from the large bubble interface. This caused multiple ultrasonic wave reflections between the transducer surface and the large bubble interface. Therefore, the interface position information appears at the intensity peak position closest to the transducer in the case of large bubble passing. Conversely, signals from multiple bubble interfaces are observed in the instantaneous echo signal when the flow direction length of a small bubble is smaller than the ultrasonic beam width (approximately 5 mm in this experiment) and there are multiple bubbles on the ultrasonic propagation axis. Each signal peak position represents a small bubble interface position in this case. The peak processing method should be switched for each bubble size; therefore, the transmitted signal from TDX1 to TDX2 was used to determine whether the reflected signal at each time was from large or small bubbles before identifying the interface position.

Figure 6 shows an example of the transmitted signal from TDX1 to TDX2 when small bubbles and large bubbles pass through. The signal transmitted through the liquid is observed in the case of a small bubble passing or no bubble exists on the propagation axis, as shown in Figure 6(a) by TDX2. In contrast, the ultrasound is blocked by the bubble surface and the transmitted signal disappears in the case of a large bubble passing, as shown

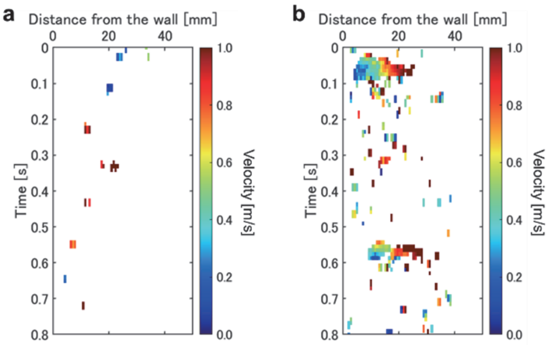

Figure 8. Spatiotemporal bubble velocity distribution measured by TDX1 (a) Air flowrate: 0.5 L/min, (b) Air flowrate: 4.5 L/min.

in Figure 6(b). The peak processing described above was applied to the reflected signals following the classification result. As the next step, the interface positions detected at TDX1 and TDX2 for small bubbles that were close in distance and similar in signal duration were considered as one small bubble. The first peak position detected at each TDX was connected for large bubbles. **Figure 7** shows the bubble distribution reconstructed by this method. A bubble flow with continuously rising bubbles was captured at the air flowrate of 0.5 L/min, and a bubble distribution representing the flow pattern of a slag flow with large bubbles and small bubbles alternately appearing was obtained at 4.5 L/min.

The velocity of each bubble was measured by the pulsed Doppler method as shown in **Figure 8**. This study used the velocity measured by TDX1 and adopted the velocity at

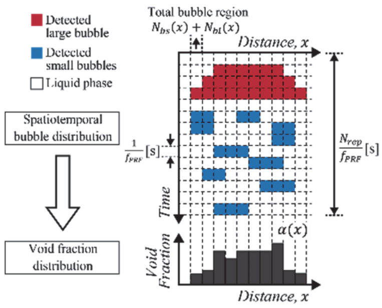

Figure 9. Schematic diagram of void fraction computation using spatiotemporal bubble distribution.

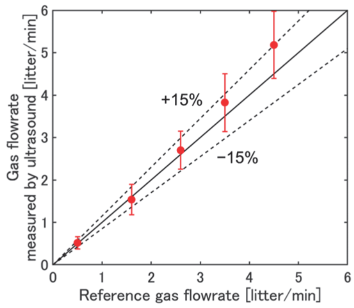

Figure 10. Result of volumetric gas flowrate measurement with ultrasound.

each intensity peak position in the next section.

4.2. Volumetric gas flowrate measurement

The bubble position, size, and velocity distribution were measured by the combination of the pulse-echo method and the pulsed Doppler method as described in section 4.1. The void fraction distribution is necessary to compute the gas volumetric flowrate by Eq. (2). The local void fraction is the ratio of the total measurement time to the sum of the gas-phase passage time, and the void fraction distribution is obtained using the spatiotemporal bubble distribution as shown in **Figure 9**, and computed by the following equation.

$$\alpha(x) = \frac{T_G}{T_{meas}} = \frac{N_s(x) + N_l(x)}{N_{rep}} \tag{10}$$

where $N_s(x)$ and $N_l(x)$ are the total small and large bubble regions at the position x in the time direction, and N_{rep} is the number of pulse repetitions, respectively. The average velocity distribution on the measurement axis $v_b(x)$ can be obtained by ensemble averaging for the instantaneous bubble velocity distribution (Figure 8). Therefore, the gas-phase volume flowrate can be calculated by substituting these parameters into Eq. (2).

Figure 10 shows the result of gas volumetric flowrate measurement by the developed system. The horizontal axis represents the reference gas flowrate measured by the float flow meter, and the vertical axis means the measured gas flowrate. The gas flowrate was computed approximately every 1.36 s and repeated 100 times at each flowrate condition. The plotted points are time-averaged values, and the error bars mean the standard deviations. Results revealed an increased relative error of the measured gas flowrate compared with the reference flowrate. The error is caused by an overestimation of the void fraction because identifying the groups of small bubbles, which were detected as large bubbles, became difficult as the void fraction increased. The sensor system should be optimized for higher ultrasonic frequencies (i.e., smaller wavelengths) to improve measurement accuracy to small bubbles and narrower ultrasonic beams to improve spatial resolution. However, the relative error was within ±15% at each flowrate, and the developed system enables gas flowrate measurement in gas–liquid two-phase flow.

5. Conclusion

This study focused on the measurement method using ultrasonic pulses to noninvasively determine the gas-phase flowrate in gas–liquid two-phase flow in a pipe and developed a measurement system combining pulse-echo and pulsed Doppler methods. The system uses these methods and an opposed transducer pair to obtain the spatiotemporal distribution of the reflected signal at the bubble interface. A signal processing method was developed that combines the reflected signal at the bubble interface and the transmitted signal in the liquid to obtain bubble distribution (bubble position and size) and bubble velocity distribution. The bubble distribution that has characteristics of bubble and slag flows in a pipe was observed by applying the method to the air–water two-phase flow. Moreover, a method to convert the distribution information to gas-phase flowrate was constructed. The measurement accuracy of the method was experimentally verified, and the relative error to the reference flowrate was within ±15%. The accuracy of the method depends on the ultrasonic beam width and wavelength concerning the bubble size. Therefore, the characteristics of the flow field when setting parameters are necessary to be considered for the actual application.

References

[1] Y. Matukuma, R. Hamaguchi and M. Minemoto, Methane hydrate recovery technology from deep seabed,, *Japanese Journal of Multiphase Flow* 36 (2022), pp. 398-406.

[2] M.H.F. Rahiman, R.A. Rahim, H.A. Rahim, E.J. Mohamad, Z. Zakaria and S.Z.M. Mujic, An investigation on chemical bubble column using ultrasonic tomography for imaging of gas profiles, *Sensors and Actuators Part B* 202 (2014), pp. 46-52.

[3] W. Wongsaroj, A. Hamdani, N. Thong-un, H. Takahashi and H. Kikura, Extended short-time Fourier transform for ultrasonic velocity profiler on two-phase bubbly flow using a single resonant frequency, *Applied Sciences* 9 (2019), pp. 1-21.

[4] Y. Takeda, Velocity profile measurement by ultrasonic Doppler shift method, *International Journal of Heat and Fluid Flow* 7 (1986), pp. 313-318.

[5] S. Wada, K. Tezuka, W. Treenuson, N. Tsuzuki and H. Kikura, Estimating the number of transducers for

flow rate measurement using the UVP method downstream of double elbows, *Flow Measurement and Instrumentation* 32 (2013), pp. 51-62.
[6] A. Povolny, H. Kikura and T. Ihara, Ultrasound pulse-echo coupled with a tracking technique for simultaneous measurement of multiple bubbles, *Sensors* 18 (2018), p. 1327.
[7] W. Wongsaroj, N. Thong-un, N. Shoji, H. Takahashi and H. Kikura, De-aliasing of ultrasonic velocity profiler on bubbly flow beyond the Nyquist limit, *Acoust. Sci. & Tech.* 41 (2020), pp. 917-920.
[8] C. Kasai and K. Namekawa, Real-time two-dimensional blood flow imaging using ultrasound doppler, *Japanese Journal of Applied Physics* 26.S1 (1987), pp. 9-13.
[9] H. Murakawa, K. Sugimoto and N. Takenaka, Effects of the number of pulse repetitions and noise on the velocity data from the ultrasonic pulsed Doppler method with different algorithms, *Flow Measurement and Instrumentation* 40 (2014), pp. 9-18.