Measurement of Solid-Gas-Liquid Three-Phase Flow using Pulsed Ultrasound

Naruki Shoji[1], Hiroshige Kikura[2], Hideharu Takahashi[3], Koji Teramoto[1], and Hideki Kawai[1]

[1] College of Design and Manufacturing Technology, Robotics and Mechanical Engineering Research Unit, Muroran Institute of Technology, 27-1 Mizumoto-cho, Muroran, Hokkaido 050-8585, Japan
[2] Laboratory for Zero-Carbon Energy, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8550, Japan
[3] School of Engineering, Department of Mechanical Engineering, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8550, Japan

In the process of transporting methane hydrate from the seafloor, a multiphase flow of methane hydrate (solid), methane gas (gas), and seawater (liquid) is generated in the recovery pipe. It is important to measure the flow ratio of each phase in the pipe in order to determine the amount of recovery and control the flow conditions. To realize the multiphase flow measurement, we focused on ultrasonic velocity profiler (UVP) and developed the measurement system. In this study, we generated a solid-gas-liquid three-phase flow (ice-air-water system) in a vertical pipe and applied the UVP to it in order to measure the multiphase flow in the pipe. An algorithm was developed to separate the velocity data of each phase by focusing on the signal intensity and spatio-temporal shape of the reflected echo signals obtained from each phase. Moreover, the validity of this method was experimentally confirmed by comparing with high-speed camera images.

Keywords: Multiphase flow, Phase identification, Signal processing, Speckle pattern

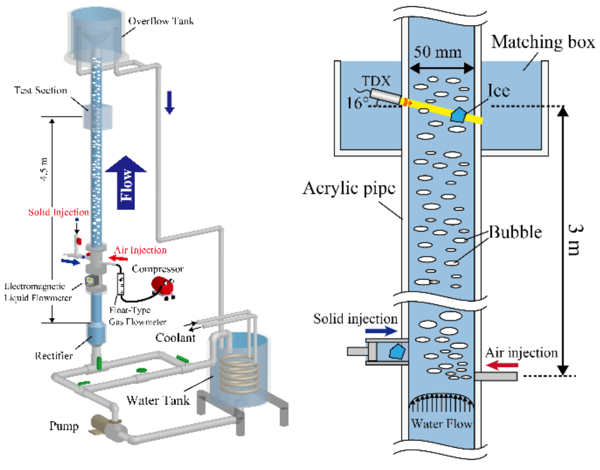
1. Introduction

Methane hydrate, which is a solid form of methane gas, is expected to be a next-generation energy resource in Japan and is believed to be stored in the deep seafloor with low temperatures and high pressures environments [1]. The methane hydrate (MH) transportation from the seafloor has attracted attention as a method using the gas-lift effect, in which gas is injected into a vertical pipe to generate an upward flow [2]. In the gas-lift method, a solid-gas-liquid multiphase flow of methane hydrate, methane gas, and muddy seawater is generated in the pipe. To optimize the pumping efficiency and assessing the status of MH recovery, the solid-gas-liquid volume ratio in the pipe should be known and the appropriate gas injection flow rate should be controlled according to the pumping conditions. However, there is no established method for measuring the solid-gas-liquid multiphase flow. It is difficult to use contact probes or other means to invasively measure the inside of the pipe because of the flow of solid phase. Moreover, a metal pipe is used as the recovery pipe, applying optical methods such as particle image velocimetry are difficult. Therefore, this study focuses on ultrasonic measurement methods that allow non-invasive measurement from outside the metal pipe and aims to develop a monitoring technique for solid-gas-liquid multiphase flow in a pipe using ultrasonic waves. In this study, ultrasonic velocity profiling method (UVP) was applied to a simulated solid-gas-liquid multiphase flow, ice-air-water system, in a vertical pipe, and features were extracted from the ultrasonic echo signals to verify whether the solid, gas, and liquid phases could be distinguished respectively.

2. Experiment

2.1 Experimental facility

To verify the feasibility of the solid-gas-liquid three-phase flow measurement using the UVP method, the pulsed ultrasonic measurement was applied to the multiphase flow and reflected echo signals were acquired. Figure 1(a) shows the test facility to generate solid-gas-liquid three-phase flow. The test facility mainly consists of a water tank, a pump, a vertical pipe (made of acrylic, inner diameter D: 50 mm), an air compressor, a gas injector, a solid injector, and an overflow tank. Tracer particles (nylon particle, mean diameter: 80 μm) were mixed in the water tank, and the pump generated an upward flow in the vertical pipe. The water flow rate was referenced to an electromagnetic flow meter installed in the flow channel. As the gas phase, compressed air was injected into the vertical pipe by the air compressor, and the gas flow rate was monitored by a float flow meter. In addition, ice was injected as the solid phase which simulated the MH. Figure 1(b) shows the schematic diagram of the measurement setup of UVP. In this experiment, the ultrasonic transducer (TDX) was installed at an angle of 16° to the pipe wall normal in a test section at 3 m from the air injection section (L/D = 60) to verify the feasibility of measuring the solid-gas-liquid multiphase flow using the UVP. A water box was placed around the test section pipe for acoustic matching to pass through ultrasonic waves into the pipe from outside the pipe. Table 1 shows the experimental conditions. During the experiment, the water flow rate and the air flow rate was kept constant at 46 litter/min and 1 litter/min, respectively. Ice was also injected from the solid injector during the ultrasonic measurement time. The size of ices was less than 30 mm.



(a) (b)

Figure 1: Schematic diagram of (a) test facility for solid-gas-liquid three-phase flow generation and (b) measurement setup.

Table 1: Experimental conditions.

Parameter	Condition
Fluid	Ice-air-water three-phase flow (with 80 µm nylon particles)
Pipe inner diameter	50 mm
Wall thickness at test section	1 mm
Water temperature	10°C
Water flowrate	46 litter/min
Air flowrate	1 litter/min
Size of ices	Less than 30 mm

2.2 Measurement system

Figure 2 shows the ultrasonic measurement system and Table 2 shows the measurement conditions for the experiment. The measurement system consists of laboratory-made ultrasonic measurement hardware [3], the hardware control and signal processing computer, and TDX (ultrasonic center frequency: 2 MHz, element diameter: 10 mm). The hardware mainly includes a high-voltage pulser for the pulsed ultrasound transmission, a variable amplifier for the received echo signal, a low-pass filter, an analog-to-digital converter (ADC), and FPGA (Field Programmable Gate Array) to control each circuit. In this experiment, ultrasonic pulses were transmitted at ±75 V, and the received echo signals were sampled by the ADC at a sampling speed of 50 MS/s and bit resolution of 12 bits. The pulse repetition frequency was set to 2000 Hz and the echo signal was recorded 8192 times consecutively in one measurement (appx. 4.2 seconds). The recorded signals were processed on the computer using MATLAB 2021a (MathWorks). Incidentally, a high-speed camera image measurement (FASTCAM Mini AX50, Photron) using the backlight method was also performed simultaneously synchronized with the pulse transmission timing (2000 fps) to identify the ultrasonic reflection source.

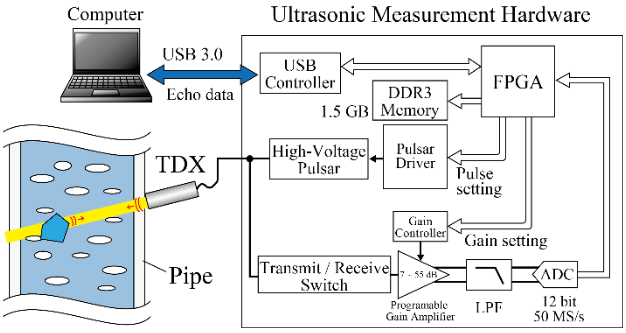


Figure 2: Schematic diagram of the ultrasonic measurement system.

Table 2: Measurement conditions.

Parameter	Condition
Sound velocity in water	1448 m/s
Ultrasonic center frequency	2 MHz
Wavelength in water	0.72 mm
Number of pulse cycles	2
Ultrasonic element diameter	10 mm
Pulse repetition frequency	2000 Hz
Incident angle	16°
Number of echo signals recorded consecutively	8192
Sampling speed of echo signal	50 MS/s

3. Phase-Separation Algorithm

3.1 Signal characteristics

To separate the solid (ice), gas (air) and liquid (water) phase velocity data of UVP, the characteristics of echo and Doppler signals were considered. First, to discriminate between the liquid phase (tracer particles) and other phases, we focused on the statistical method based on the reflected echo signal intensity using the reflectance of each phase [4]. The acoustic reflectance can be described by

$$R = \frac{Z_1 - Z_2}{Z_1 + Z_2} = \frac{\rho_1 c_1 - \rho_2 c_2}{\rho_1 c_1 + \rho_2 c_2} \quad (1)$$

where Z represents acoustic impedance, c is sound velocity, and ρ is the density, respectively. The reflectance R of the gas-liquid interface is greater than the small particle-liquid interface significantly. Thus, the echo intensity reflected from a gas-phase is larger than from a particle. In addition, echo intensity also depends on the reflector size. If the reflector size is larger than the ultrasonic beam diameter, higher echo intensities are observed. Therefore, liquid phase can be identified by thresholding to echo intensity. Next, we examined a method for discriminating between the solid and gas phases. Figure 3 shows example of spatio-temporal plots of high-speed camera and ultrasonic echo signal intensities in bubbles and ice obtained experimentally. In each figure, the horizontal axis represents measurement time, t, and the vertical axis represents the distance from the TDX surface, x. The echo intensity was determined by the following equation:

$$A(t,x) = \sqrt{s^2(t,x) + \{H(s(t,x))\}^2} \qquad (2)$$

where s is the echo signal, and H represents the Hilbert transform. As shown in Figure 3(b), the spatio-temporal intensity distribution of the signal reflected from the bubble interface was short in the distance direction and had high signal intensity. In contrast, as shown in Figure 3(d), the spatio-temporal intensity distribution of the signal reflected from ice has a high signal intensity at the ice interface and a complex speckle pattern. Considering the ultrasonic propagation paths in the case of bubbles and solids as flowing reflectors, as shown in Figure 4, the reflectance at the bubble interface is approximately 1 from Eq. (1), and the signal width of the reflected echo is equal to the transmitted pulse width. On the other hand, in the solid phase, it is reflected at the solid interface and incident from the liquid phase into the solid phase. This causes multiple reflections in the solid. The reflected waveforms are superimposed and interfere with each other. In addition, because the solid rotates and moves with the flow, the interference waveform shape changes with time. As a result, a speckle pattern appears in space-time. Therefore, the gas and solid phases can be distinguished by detecting this speckle.

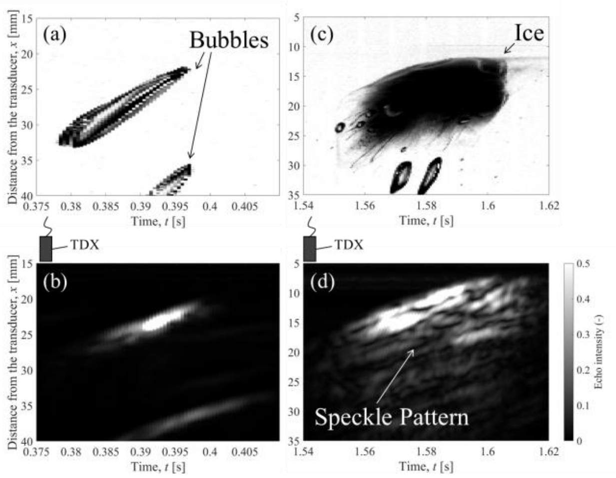


Figure 3: Example of spatio-temporal plots of high-speed camera and ultrasonic echo signal intensities in bubbles and ice. (a) high-speed camera image and (b) echo intensities in bubbles. (c) high-speed camera image and (d) echo intensities in ice.

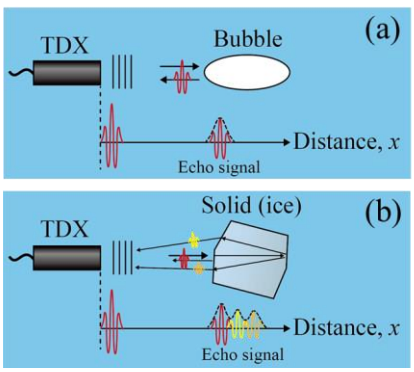


Figure 4: Ultrasonic propagation path in gas and solid phases.

3.2 Speckle detection

To discriminate between solid and gas phases, speckle was detected from the signal. Speckles are generated by the interference of diffusely reflected components in the solid phase, so multiple peaks of signal intensity appear in the time direction and the intensity decay is slow. In contrast, the gas phase is totally reflective at the interface, resulting in a relatively sharp single peak. Then, a moving time window was set for the Doppler signal intensity, and the autocorrelation function was calculated for the window. When the decay is slow and multiple peaks appear, the fall of the correlation value with respect to the time lag is slow. By evaluating the decay time of the correlation value, it is possible to determine the speckle (identify the solid and gas phases). Where the received echo signal at transmission timing, t, and reflected position, x, is s (t, x), the echo signal is represented as follow:

$$s(t,x) = A(t,x)\cos\{4\pi(f_c + f_D)x/c\} \qquad (3)$$

where c is sound velocity, A is signal intensity, f_c is ultrasonic center frequency and f_D is the Doppler frequency, respectively. By applying quadrature demodulation to Eq. (3), a complex Doppler signal z (t, x) containing only the Doppler frequency component is obtained.

$$\begin{aligned} z(t,x) &= \mathrm{LPF}\left[s(t,x)\cos\left(\frac{4\pi f_c x}{c}\right)\right] \\ &\quad + j\mathrm{LPF}\left[s(t,x)\sin\left(\frac{4\pi f_c x}{c}\right)\right] \\ &= A_D(t,x)e^{-j4\pi f_D x/c} \end{aligned} \qquad (4)$$

where LPF[] represents the low-pass filtering process for the signal in bracket [], A_D is the Doppler signal intensity, and j is imaginary unit. As in Eq. (2), the Doppler signal intensity is obtained by applying the Hilbert transform. Figure 5 shows the example of Doppler signal and its envelope. The signal from the bubble had a clear peak, while the signal from the ice had a complex envelope shape due to interference.

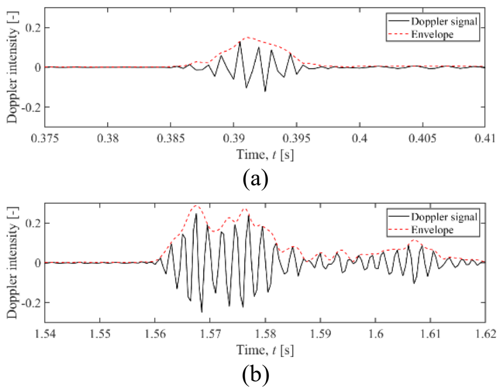


Figure 5: Example of Doppler signal and its envelope shape. (a) signal from a bubble, (b) signal from an ice.

An autocorrelation function is applied to the envelope within a certain time range, t_1 to t_2.

$$r(\tau) = \frac{1}{r(0)}\int_{t_1}^{t_2} A_D(t,x)A_D(t-\tau,x)dt \qquad (5)$$

As shown in Figure 6, the decay time of auto correlation coefficient was different between solid and gas phase. Thus, phase identification is possible by using the descending time of the coefficient as an evaluation function. Where the time until the coefficient is halved is τ_h, the evaluation function that discriminates between the solid and gas phases is expressed by the following equation.

$$J_{SG} = \frac{1}{\tau_h + 1} \quad (6)$$

These processes were applied to echo signals of Figure 3, and Figure 7 shows the identification results. In Figure 7, the color represents the probability of solid phase, which is normalized by the maximum value of the evaluation function in Eq. (6). The solid and gas phases were successfully discriminated.

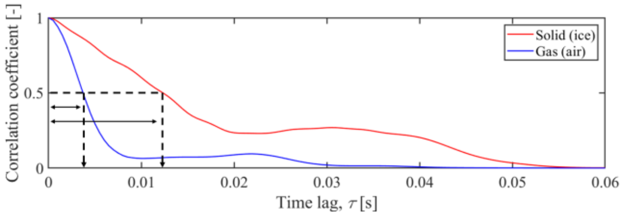
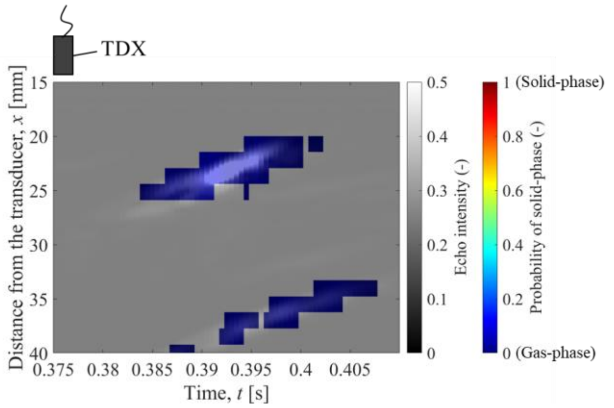
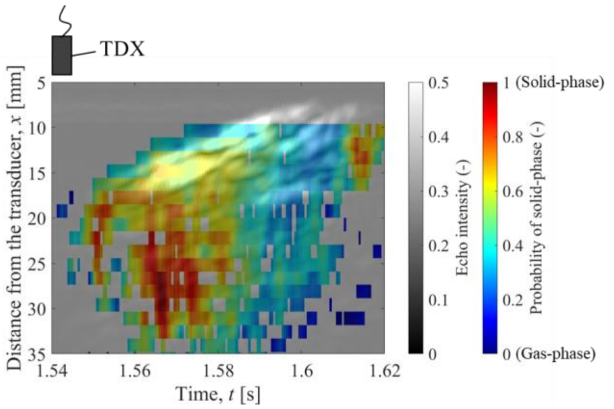


Figure 6: Comparison of auto correlation coefficient of Doppler signal envelope between solid (ice) and gas (air).



(a)



(b)

Figure 7: Results of solid and gas phase identification. (a) signal of bubble, (b) signal of ice.

4. Results and Discussion

Figure 8 shows the instantaneous velocity profile of each phase detected using the Doppler signal separated by the phase identification algorithm. Center graph is solid phase velocity profile, and bottom is bubble velocity profile, respectively. Velocity data were obtained at each phase location. The velocity profile of the solid phase was compared with that obtained by time-of-flight method using high-speed camera images; the spatial averaged solid phase velocities measured by UVP were 456, 459, and 424 mm/s for #1 to #3, respectively, and 475, 515, and 437 mm/s for the high-speed camera. The relative error was within 3-10 %, the validity of the developed method was confirmed.

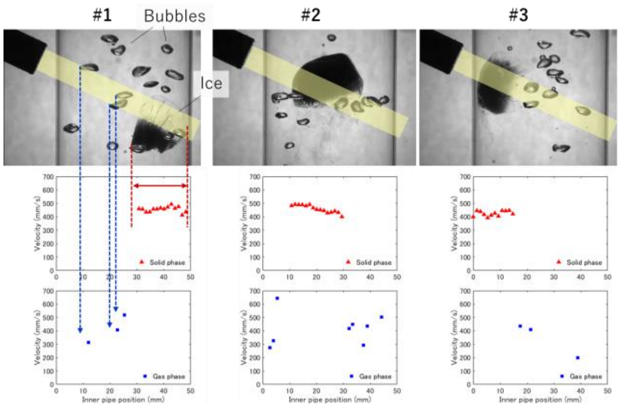


Figure 8: Instantaneous velocity profiles of each phase.

5. Summary

To realize the multiphase flow measurement with the UVP, solid-gas-liquid three-phase flow (ice-air-water system) in a vertical pipe was generated and the UVP measurement was applied to it. To identify the velocity data of each phase, the signal characteristics were extracted. The liquid phase (water) and other phases are separable by echo signal intensity, and the solid phase (ice) and gas phase (air) are shown to be potentially discriminable by detecting the speckle patterns formed in spatio-temporal signal intensity distribution. The method presented in this paper is affected by a combination of conditions such as solid phase size, acoustic impedance, ultrasonic frequency and element size. In the future, we will organize these influences and improve the measurement accuracy.

References

[1] Agency for Natural Resources and Energy of METI HP: https://www.enecho.meti.go.jp/about/special/johoteikyo/methanehydrate.html (2017)

[2] Matukuma Y, *et al.*: Methane Hydrate Recovery Technology from Deep Seabed, Japanese J. Multiphase Flow 36 (2022), 398-406.

[3] Shoji N, *et al.*: Leakage Detection and Flowrate Estimation With Three-Dimensional Vector Ultrasonic Velocity Profiler, Proceeding of the 12th Japan-Korea Symposium on Nuclear Thermal Hydraulics and Safety (2022), 1-5.

[4] Wongsaroj W, *et al.*: 2D velocity vector profile measurement on bubbly flow using ultrasonic technique, Mechanical Engineering Journal 7 (2020), 1-15.