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Measurement of steam flow rates using a clamp-on ultrasonic flowmeter with various wetness fractions

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Abstract

Most of the heat in industrial plants is supplied by steam. To minimize energy waste, measuring the steam flow rates in existing pipes is important. Clamp-on ultrasonic flowmeters are used for this purpose, for which the sensors are attached to the pipe wall. However, flow conditions that can be used are limited because the signal-to-noise ratio of the ultrasonic signal in a steam flow is low. Furthermore, the steam wetness increases with heat losses, which may affect measurement results. Therefore, flow rate measurements in wet steam flows using clamp-on ultrasonic flowmeters have not been fully established. In this study, steam flow rates with various wetness fractions and system pressures were measured using a laboratory-made clamp-on ultrasonic flowmeter. The results show that flow rates in wet steam could be determined within a 10 % error under general conditions in a steam piping system, although the conversion factor from line-average to area-average velocities was calibrated in superheated conditions, and the speed of sound in saturated conditions at each pressure was used. However, the error of the flow rates tended to increase with the wetness fraction and was biased toward positive values. The speed of sound and liquid volume fraction were evaluated at different wetness fractions. The flow rate error due to the change in sound speed was less than 1 %, and 1.2 % of the flow rates were overestimated owing to the liquid volume fraction. The velocity distribution in wet steam was considered different from that in the superheated steam owing to the existence of the liquid phase, and the change in velocity profile may lead to an overestimation of the steam flow rates in the wet steam condition.

Keywords: wet steam, speed of sound, clamp-on ultrasonic flowmeter, time of flight, wetness fraction, velocity distribution

1. Introduction

The heat demands in industrial plants are high, and most of the heat are supplied by steam using a piping system to each consumption point. The required flow rates of steam at different points of consumption may vary frequently, and a part of the steam may condense through the piping system because of heat loss, resulting in a decreased steam flow rate. Therefore, controlling the steam flow rate to satisfy the heat demand is difficult, and excessive steam is generally supplied from boilers, due to which a large amount of heat energy is wasted. To optimize the steam supply, the saturated or wet steam flow rates in the existing pipe near the consumption places must be measured.

Gas or steam flow rates are generally monitored using orifice, vortex, and in-line ultrasonic flowmeters [1]. Several studies have been conducted on these flowmeters for measuring wet steam flow rates [2, 3]. Clamp-on ultrasonic flowmeters have the potential to be applied to existing pipes. Therefore, they have been widely used in industrial plants for measuring liquid and gas flow rates [4]. Their principle is based on the time-of-flight (TOF), which changes with the flow velocity along the propagated ultrasonic pulses. Thus, flow rate is obtained based on the transit time difference of the ultrasonic pulses between upstream and downstream sensors. To measure the flow rate accurately, the transmitted ultrasonic signals must be detected. However, the measurement is difficult in the case of steam flow because ultrasonic attenuation in steam is higher than in liquid. Furthermore, the large difference in the acoustic impedance between the pipe material and steam results in a lower intensity of the transmitted ultrasonic signal for clamp-on ultrasonic flowmeters. Thus, measuring liquid flow rates is easier than measuring gas flow rates using the clamp-on system. To improve the signal-to-noise ratio (SNR) of the transmitted ultrasonic signal, a sensor with a curved shape for gas flow rate measurement was developed [5]. However, high temperatures cause a decrease in the sensitivity of piezoelectric elements and a resulting decrease in the SNR. The existence of the liquid film and droplets due to the heat loss may also affect the SNR. These factors make it difficult to measure the flow rate of steam, especially wet steam, using the clamp-on ultrasonic flowmeters. To improve the SNR for steam flow measurement, an ultrasonic sensor and a damping material made of silicon rubber were developed [6, 7]. The latter can reduce the propagated ultrasound signal inside the wall, resulting in an increase in the SNR. The angle between the wedge and pipe surface is also an important factor for increasing the intensity of the ultrasonic transmission. To increase the SNR, Lamb waves producing a wide beam have been widely used for measuring gas flow rates [8]. Murakawa et al. developed a standard deviation (SD) method to detect the transit time difference accurately under a low-SNR condition in two-phase flows in adiabatic conditions [9]. Their study shows the forms of the SD representing the flow regime. Murakawa et al. [10] also investigated the effect of the incident angle of ultrasound on the intensity of the transmitted signal in steam flows using a variable incident-angle transducer. Their results showed that the measurement accuracy of the flow rate and SNR must be greater than 9 dB for accurate flow rate measurements.

There are many factors that affect the measurement uncertainties using the ultrasonic flowmeters, such as the sensor installation, pipe roughness, speed of sound in the fluids etc. [11], which have been studied for measuring liquid and gas flows [12, 13]. However, studies on the effect of wetness in wet steams on the flow rate measurements are few. Furthermore, applicability of the clamp-on ultrasonic flowmeters to the wet steam flow is not yet clarified due to the measurement difficulty. For flow rate measurements in wet steams, the conversion from the transit time difference to the flow rate should be considered. As the transit time difference is converted to the area-average velocity in the TOF flowmeter, the existence of the liquid phase may affect the measurement results. Considering the volume fraction of the liquid phase in a wet steam, Morita et al. [14] and Uchiyama et al. [15] proposed correction methods to obtain the steam flow rate from ultrasonic flowmeters. To calculate the flow rates of the gas phase from the measured values in horizontal two-phase flows using an in-line ultrasonic flowmeter, Xing et al. [16] employed a slip ratio model by Lockhart & Martinelli. The transit time difference depends not only on the flow velocity but also on the speed of sound in the flow. However, the speed of sound in wet steam may change with steam quality [17]. Michaelides and Zisis [18] developed a calculation method for the speed of sound in two-phase mixtures in thermodynamic equilibrium. Collingham and Firey [19] measured the speed of sound in wet steam by changing the steam quality using a water spray nozzle. They showed that the speed of sound was independent of the quality and approximately equal to that in saturated steam. Moreover, the speed of sound in wet steam slightly decreased with the steam quality under the condition of fog flow [20]. Shen [21] attempted to evaluate the steam quality based on the speed of sound using a TOF ultrasonic flowmeter. However, the dependency of steam quality on the speed of sound and effect on the flow rate measurements have not been fully understood. For these reasons, clamp-on ultrasonic flowmeters have been used for measuring a limited condition in steam flow, i.e., saturated steam.

In a real situation, the wetness fraction in a steam flow is usually unknown. Therefore, the evaluation of the measurement results and understanding of the error factors are important for estimating the actual steam flow rate in industrial plants. However, the effect of wetness fraction on the measurement accuracy are not fully understood. The objective of this study is to establish a clamp-on ultrasonic flowmeter for measuring wet steam flow rates and to evaluate the wetness effect on the flow rate measurements. Thus, in this study, steam flow rates were measured under various wetness fractions and system pressures using a clamp-on ultrasonic flowmeter. The SD method was employed for measuring the flow rate at low system pressure condition, and the error factors of flow rate measurement in wet steam were examined. The cause of the flow rate error with respect to the change in the speed of sound in wet steam, effect of the liquid volume ratio, and change in the conversion factor from the transit time difference to the flow rate was also discussed.

2 Methodology

2.1 Principle of TOF ultrasonic flowmeter

The basic principle of the TOF flowmeter as presented in the literature [9, 10] is schematically shown in Fig. 1. For the clamp-on type ultrasonic flowmeter, ultrasonic transducers composed of a wedge and piezoelectric element are used for the ultrasonic pulse emissions and receptions. A pair of the ultrasonic transducers is installed at upstream and downstream positions on the external surface of the pipe. Ultrasonic pulses propagate from the wedge to the pipe with an incident angle of θ_1 and from the pipe to the fluid with a refraction angle of θ_2. The relationship among the speed of sound, θ_1, and θ_2 are determined by Snell's law as follows:

$$\frac{\sin\theta_1}{c_\mathrm{m}} = \frac{\sin\theta_2}{c_\mathrm{f}}, \tag{1}$$

where, c_m is the speed of sound in the wedges, and c_f is that in the fluid.

When an ultrasonic pulse traverses from the upstream to downstream direction, the transit time of the ultrasonic signal, t_1, becomes shorter depending on the flow velocity, whereas that from the downstream to upstream direction, t_2, becomes longer as expressed in the following equations:

$$\begin{aligned} t_1 &= (D/\cos\theta_2)/(c_\mathrm{f} + V_\mathrm{L}\sin\theta_2) + t_0, \\ t_2 &= (D/\cos\theta_2)/(c_\mathrm{f} - V_\mathrm{L}\sin\theta_2) + t_0, \end{aligned} \tag{2}$$

where D is the inner diameter of the pipe, V_L is the line-average velocity along the ultrasonic beam, and t_0 is the transit time of the ultrasonic signals propagating from the transducers through the pipe walls. To neglect t_0, the transit time difference, Δt, is calculated as follows:

$$\Delta t = t_2 - t_1 = \frac{2DV_L\tan\theta_2}{{c_\mathrm{f}}^2 - V_\mathrm{L}^2\sin^2\theta_2}. \tag{3}$$

The flow rate, Q, is calculated from V_L as

$$Q = \frac{\pi D^2}{4}\cdot V = \frac{1}{K}\cdot\frac{\pi D^2}{4}\cdot V_\mathrm{L} \tag{4}$$

where K is a conversion factor from V_L to the area-average velocity, V. It is well known that K depends on the velocity profiles.

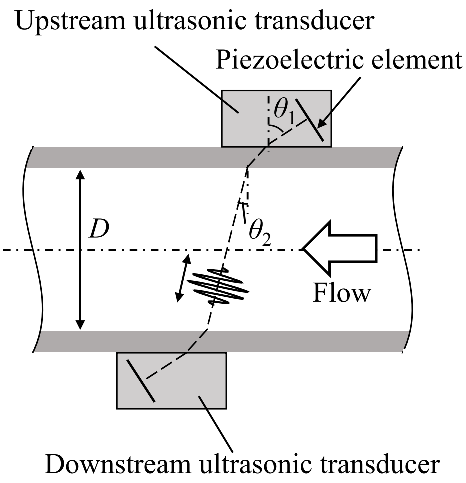


Fig.1 Schematic diagram of a clamp-on ultrasonic flowmeter (top view).

2.2 Experimental facility and conditions

The flow loop used was the same as that used in our previous study [10] (shown in Fig. 2). Saturated steam was supplied from a boiler (model: AI-2000 25H, Miura Co. Ltd., Japan). The steam wetness was adjusted using a heater and a cooling coil, and the steam was circulated through the test section. The steam was fully condensed at the heat exchanger downstream of the test section, and the total mass flux, G_{total}, was measured using the Coriolis flowmeter. Pressure control and backpressure valves were used to control the system pressure and flow rate, respectively. The wetness fraction, β, was calculated based on the steam pressure, steam temperature, and inlet and outlet temperatures of the cooling water. The reference area-average velocity of the steam flow, V_{ref}, was calculated as

$$V_{\mathrm{ref}} = \frac{G_{\mathrm{total}}}{A\rho}, \tag{5}$$

where A denotes the cross-sectional area of the pipe, ρ denotes the density. ρ_{wet} and ρ_{sup} are the densities of wet steam and superheated steam, respectively. In the wet steam condition, the homogeneous flow model was applied, for which the density is expressed as

$$\frac{1}{\rho_{\mathrm{wet}}} = \frac{1-x}{\rho_{\mathrm{L}}} + \frac{x}{\rho_{\mathrm{G}}}, \tag{6}$$

where x is the gas quality; ρ_{L} and ρ_{G} are the liquid and gas densities in the saturated condition, respectively.

An SGP 65A black pipe (carbon steel pipe, outer diameter: 76.3 mm, inner diameter: 67.9 mm, shear and longitudinal wave speeds of sound = 3,230 and 5,890 m/s, respectively) without coating was used as the test section. The pipes are generally used for the piping system of the steam flow in industrial plants. The total length of the horizontal test section was 4,350 mm (64*D*). Two ultrasonic transducers were horizontally set on the outer surface of the test section, facing each other at 2,150 mm (32*D*) from the 90° elbow placed at the inlet of the test section. All pipes were insulated except for the measurement position. Ultrasonic pulses transmitted from the transducers propagate through the pipe wall and enter the fluid. It is thought that the ultrasound propagates through the pipe material as a Lamb wave [10]. A part of the ultrasound reflects on the wall–fluid interface. These signals propagate inside the pipe wall and are received at the opposite transducer. Thus, these signals are noise sources referred to as guided waves. If the intensity of the guided wave is high, the detection of the signal propagated through the fluid becomes difficult. A silicon rubber with thickness of 0.2 mm (Shin-Etsu Chemical Co., Ltd.) was set as the damping material on the outer surface of the test section as shown in Fig. 3. By setting the damping material on the pipe surface, a part of the guided wave is transmitted to the damping material, thus resulting in the attenuation of the guided wave. Based on the calibration tests in superheated steam conditions, θ_1 was determined as 53.6° by assuming that the speed of sound in the polyetherimide wedge was 2,450 m/s.

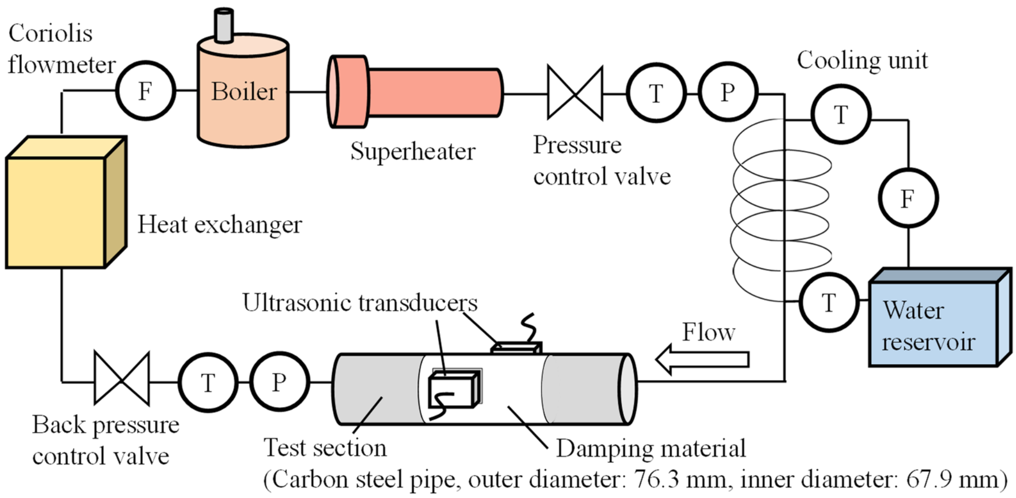


Fig. 2 Schematic of the experimental setup for wet steam flow measurement.

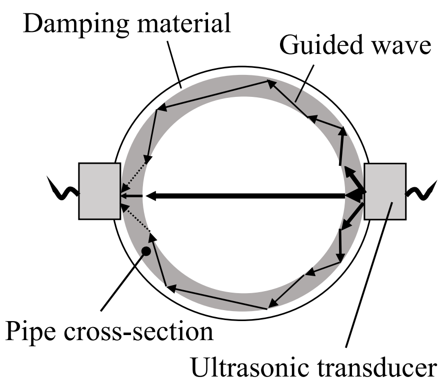


Fig. 3 Schematic diagram of the attenuation of the guided wave due to the damping material placed on the outer surface of the test section.

The experimental conditions are listed in Tables 1 and 2. The system pressure, P, ranged between 0.34 and 0.71 MPa for the superheated steam flow with different V_{ref}. The degree of superheat was between 4 ºC and 31 ºC. The speed of sound in the superheated steam was obtained using the NIST Reference Fluid Thermodynamic and Transport Properties Database [22]. For wet steam conditions, the system pressure and β ranged between 0.21 and 0.80 MPa and between 2 % and 21 % with different V_{ref}, respectively. These conditions were determined based on the actual steam flows in the piping system. The speed of sound was assumed to be that of saturated steam and obtained from steam tables based on the International Association for the Properties of Water and Steam Industrial Formulation 1997 [23]. Morita et al. [14] evaluated the extended uncertainty of the steam flow loop to be 0.61 % (coverage factor $k = 2$).

Table 1 Experimental conditions in the superheated steam flow

Pressure [MPa]	Temperature [ºC]	Reference area-average velocity, V_{ref} [m/s]	Degree of superheat [ºC]
0.34 (0.33~0.35)	150.8	12.1	12.2
	161.9	21.9	23.9
	168.2	32.2	31.0
0.51	156.5	9.6	4.1
	172.4	20.3	19.9
	170.5	31.5	18.3
0.71	169.4	9.8	4.1
	174.7	20.3	9.47
	177.0	30.5	11.5

Table 2 Experimental conditions in the wet steam flow

Pressure [MPa]	Saturated steam temperature [ºC]	Steam Temperature [ºC]	Reference area-average velocity, V_{ref} [m/s]	Wetness fraction [%]
0.21	122.5	121.3–124.3	27.3–39.4	3.60–21.47
0.33	137.0	136.3–138.0	20.0–31.6	3.44–17.47
0.50	152.0	152.1–153.0	20.1–30.1	3.13–19.31
0.70	165.0	164.0–165.9	10.5–30.1	2.00–18.49
0.80	170.5	170.2–170.6	10.2–20.5	3.91–7.43

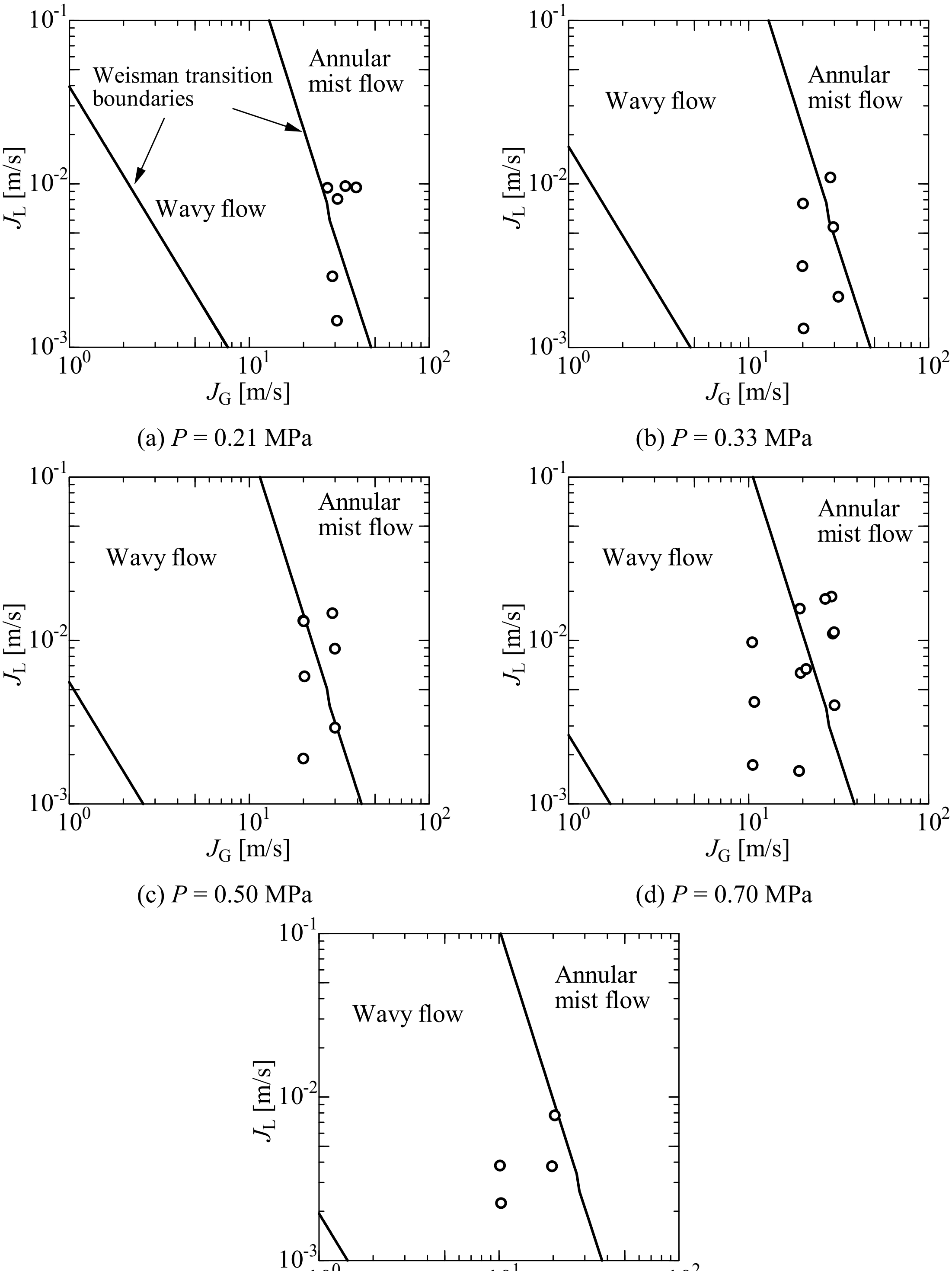
Fig. 4 shows the flow regime maps for the experimental conditions of each system pressure. Transition boundaries of the stratified–wavy and wavy–annular proposed by Weisman et al. [24] are indicated in the figure. These are given by

$$\left(\frac{\sigma}{gD^2(\rho_\mathrm{L}-\rho_\mathrm{G})}\right)^{0.20}\left(\frac{DG_\mathrm{G}}{\mu_\mathrm{G}}\right)^{0.45} = 8\left(\frac{J_\mathrm{G}}{J_\mathrm{L}}\right)^{0.16} \quad \text{for the stratified–wavy transition}$$

$$1.9\left(\frac{J_\mathrm{G}}{J_\mathrm{L}}\right)^{1/8} = \mathrm{Ku}^{0.2}\mathrm{Fr}^{0.18} = \left(\frac{J_\mathrm{G}{\rho_\mathrm{G}}^{1/2}}{[g(\rho_\mathrm{L}-\rho_\mathrm{G})\sigma]^{1/4}}\right)^{0.2}\left(\frac{{J_\mathrm{G}}^2}{gD}\right)^{0.18} \tag{7}$$

for the wavy–annular transition,

where g denotes the acceleration due to gravity, μ denotes the fluid viscosity, G denotes the mass flux, J denotes the superficial velocity, and σ denotes the surface tension. Ku is the Kutateladze number, and Fr is the Froude number. Subscripts L and G represent the liquid and gas phases, respectively. Based on the maps, the flow regimes could be wavy flow or wavy–annular transition.



(a) P = 0.21 MPa

(b) P = 0.33 MPa

(c) P = 0.50 MPa

(d) P = 0.70 MPa

(e) P = 0.80 MPa

Fig. 4 Experimental conditions on the flow regime maps proposed by Weisman et al. [24].

2.3 Experimental procedure

The same measurement system used in our previous studies [9, 10] was used in this study. A pulser/receiver (model: JPR-10C-2CH-KB, Japan Probe Co. Ltd., Japan) was connected to the ultrasonic transducers and used to emit and receive the ultrasonic pulses. The center frequency of the ultrasonic transducers was 1 MHz. Ultrasonic pulses were emitted from a transducer and the signal was received by the other transducer. The excitation peak-to-peak voltage, V_{pp}, was set at 100 V. The signals were continuously sampled using a high-speed digitizer (model: NI PXI-5114, National Instruments Corporation, U.S.A.) in each direction: from the upstream to downstream transducers and vice versa. The sampling rate was set at 250 MS/s (mega-samples per second). A total of 1,000 waveforms were recorded in each direction. The ensemble-average waveforms, $\overline{W}(t)$, and SDs of the waveforms, $W_{\mathrm{std}}(t)$, were calculated from the consecutive signals in each direction as part of post-processing.

The transit time difference between the ultrasonic signals transmitted from the upstream and downstream transducers, Δt, was determined using the normalized cross-correlation function, $R(\tau)$, as follows:

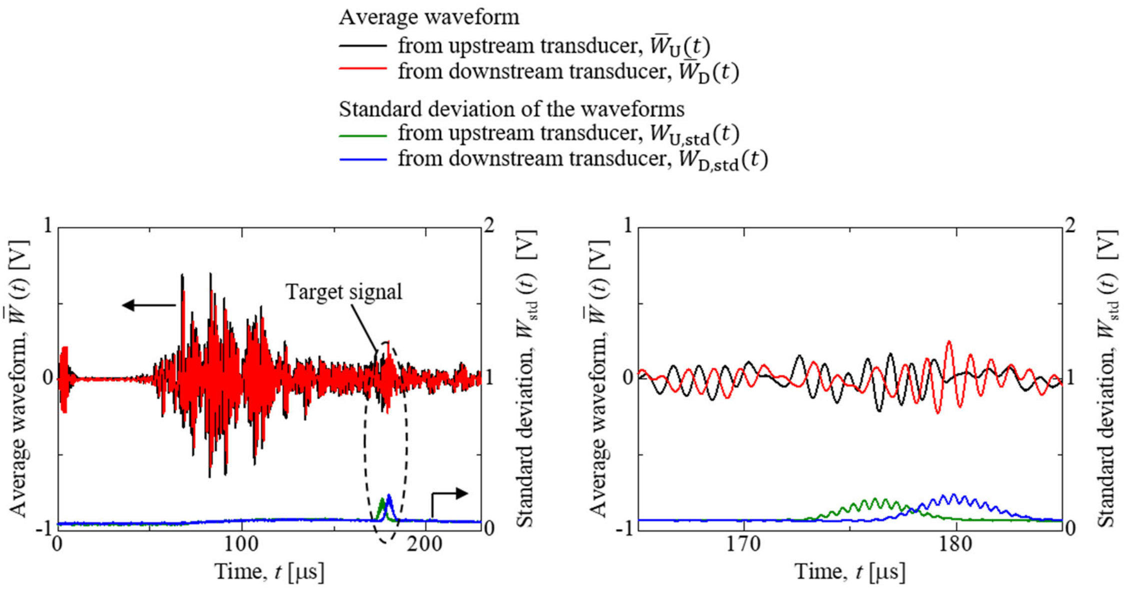
$$R(\tau) = \frac{\int E_{\mathrm{U}}(t) E_{\mathrm{D}}(t+\tau) dt}{\sqrt{\int E_{\mathrm{U}}(t)^2 dt \int E_{\mathrm{D}}(t+\tau)^2 dt}} \quad (8)$$

where E_{U} and E_{D} represent the signals, that is, $\overline{W}(t)$ or $W_{\mathrm{std}}(t)$. Subscripts U and D signify the received from the upstream and downstream transducers, respectively. The value of τ at which $R(\tau)$ is maximum is defined as Δt. V_{L} was determined for each condition using Δt from Eq. (3).

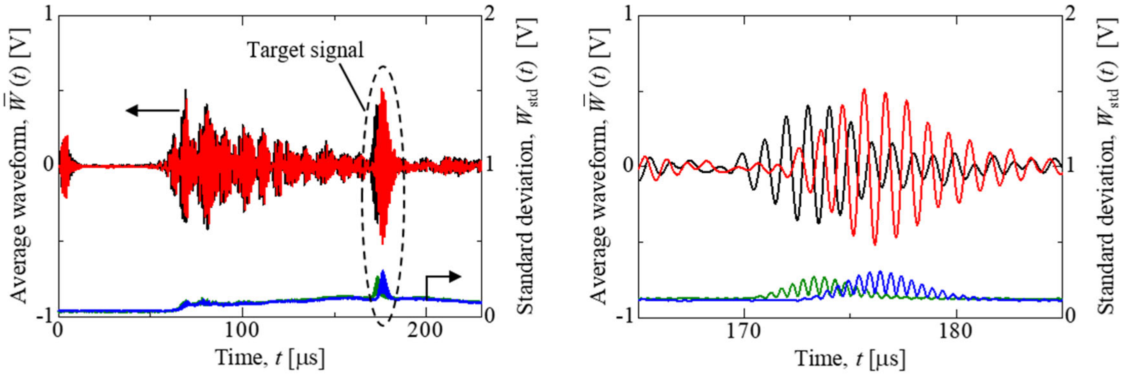
3. Results

3.1 Received waveforms and their SD

Fig. 5 shows examples of the ensemble-average and their SDs in the wet steam flow at P = 0.21 and 0.70 MPa. Ultrasonic signals transmitted from the upstream and downstream ultrasonic transducers are overlapped in each figure. The figures on the left show waveforms of the entire measurement time, and those on the right show the enlarged views around the target signal. The horizontal axis represents the time elapsed, t, from the pulse emission. Signals with high intensity are confirmed at $t < 5$ μs, which are noises associated with the pulse emission as the transmitter and receiver transducers were connected to the same pulser/receiver. Therefore, the signals were neglected. Signals with high intensities appeared again at $t > 50$ μs. The speed of sound in carbon steel is much higher than that in the steam. Thus, guided waves propagated in the pipe wall appeared at an earlier time than that propagated in the steam. Because there are many propagation paths inside the pipe wall, the guided waves are confirmed in the wide range of the elapsed time. For P = 0.70 MPa, the target ultrasonic signals propagated through the wet steam flow are confirmed at approximately 175 μs. The SNR of the signal is approximately 16 dB. The target signals can be confirmed because the signal transmitted from the upstream appeared earlier than those from the downstream owing to the flow velocity. Ultrasonic attenuation in the steam flow increased with decreases in the system pressure and increases in the flow velocity. Although the target signals were confirmed at P = 0.21 MPa, the received signal did not form an ideal burst signal, such as that at P = 0.70 MPa. The SNR was approximately 6 dB, which is insufficient for accurate flow rate measurement [10]. In this case, a misdetection of Δt likely occurred. Furthermore, the SDs of the target signals formed a convex shape and were clearly confirmed at P = 0.21 MPa. If the signal is not time dependent, then SD should be zero. However, SDs are not generally zero owing to white noises generated inside the measurement system. Therefore, SDs are expected to take a constant value irrespective of t in a real system. Furthermore, the instantaneous line-average velocity along the ultrasonic beam has slight variations due to the flow turbulence [25]. This causes the slight change of the TOF in the target signal and results in a convex shape of the target signal in the SDs. Murakawa et al. [9] developed an SD method to determine the target signals and to calculate the transit time difference for clamp-on ultrasonic flowmeters in two-phase flows. The calculation of the transit time difference based on the SD distribution is more useful than the average waveform at a low SNR. In this study, $W_{\mathrm{std}}(t)$ was used for P = 0.21 MPa, and $\overline{W}(t)$ was used for the other pressure conditions to calculate τ in Eq. (8).



(a) P = 0.21 MPa, V_{ref} = 30.8 m/s, β = 3.6%



(b) P = 0.70 MPa, V_{ref} = 19.2 m/s, β = 2.0%

Fig. 5 Ensemble-average ultrasonic signals transmitted from the upstream and downstream ultrasonic transducers and their standard deviations in wet steam flows at different pressures; figures on the right show the enlarged views around the target signal.

3.2 Determination of the K factor

Calibration tests were performed in superheated steam flows at P = 0.34, 0.51, and 0.71 MPa. V_L was calculated using the measured Δt in Eq. (3), and the K factors were obtained by assigning V_{ref} to V in Eq. (4) for each condition. Fig. 6 shows the relationship between V_{ref} and the K factor in the superheated steam flow. The K factors were distributed within ±2 %. It is well known that the velocity distribution changes with the Reynolds number, Re. Therefore, the K factor also changes with Re. Birger [26] proposed a correlation of the K as follows:

$$K = 1 + 0.01\sqrt{6.25 + 431Re^{-0.237}} \tag{9}$$

In our experiments, Re ranges between 1.9×10^5 and 1.9×10^6 in superheated and wet steam flows. Based on Eq. (9), K will vary from 1.045–1.055 accordingly. Therefore, the effect of the change in Re on K is within the range of the measurement error in Fig. 6. Furthermore, the variance between each pressure may be caused by the change in the sound speed in the wedge. Owing to a lack of information on the temperature dependence of the sound speed of the wedge material, K was determined to be 1.055 by averaging the obtained K factors.

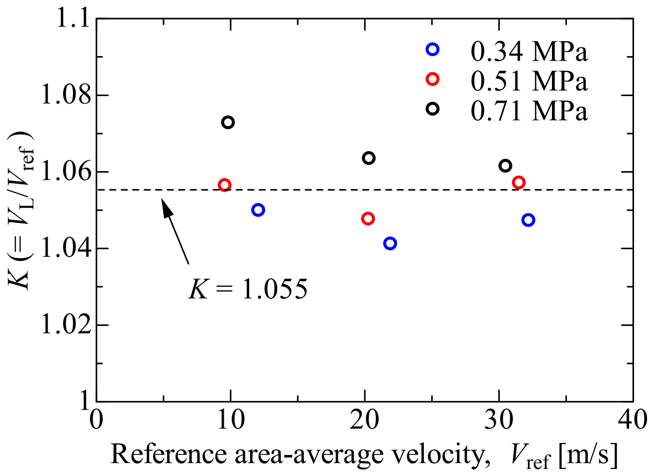
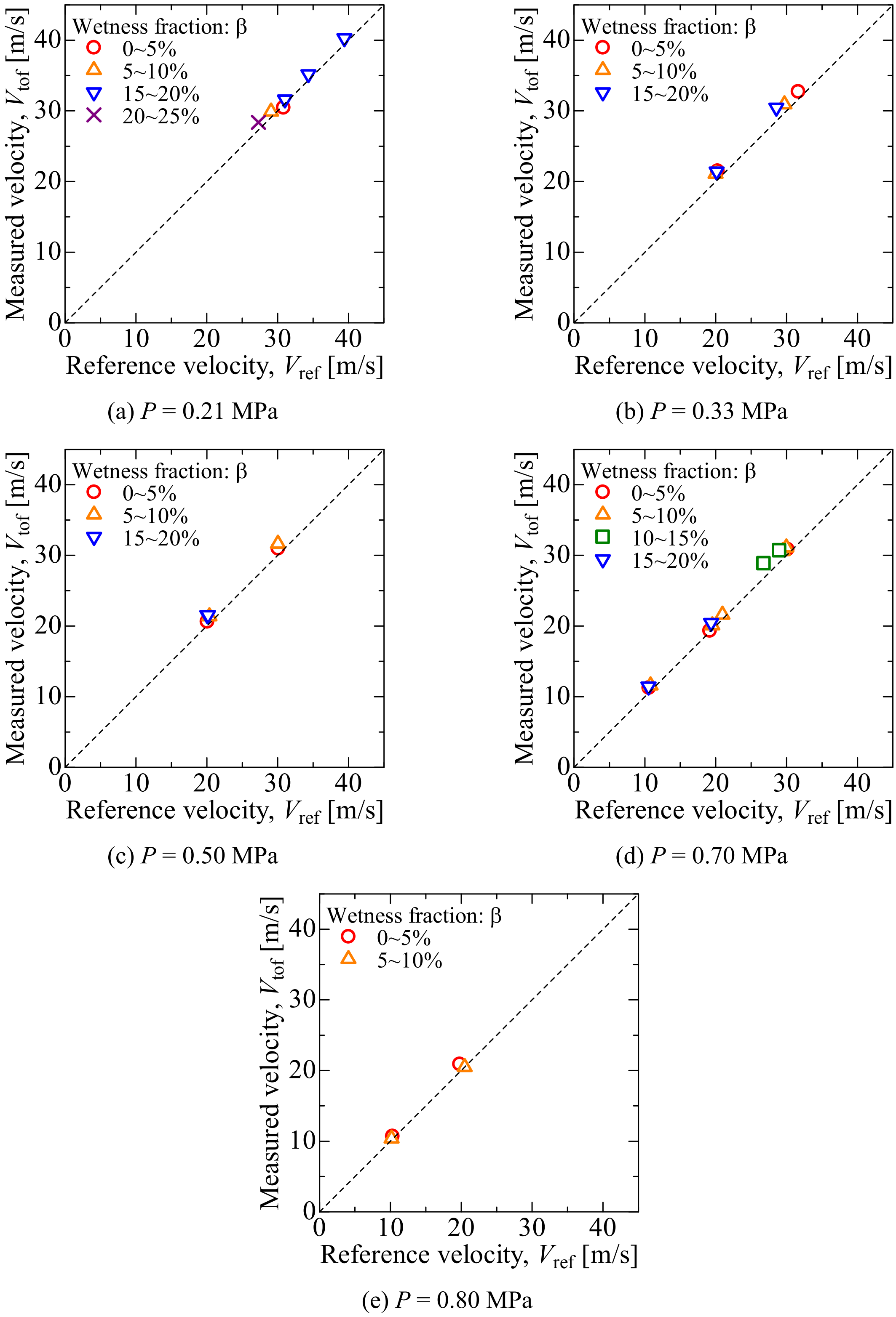


Fig. 6 Relationship between V_{ref} and K in the superheated steam flows.

Fig. 7 shows the relationship between the reference and measured velocities. The vertical axis represents the measured area-average velocities, V_{tof} ($= V_L/K$), calculated from the measured Δt. In each figure, each range of the wetness fraction is shown using different symbols. The effect of steam wetness, *i.e.*, the liquid droplet and liquid film on the wall, was excluded in the V_{tof} calculation, assuming that Δt is mainly related to the steam velocity. V_{tof} corresponds well to V_{ref}, although V_{tof} is slightly larger than V_{ref} in some conditions. For easy understanding, the error ratio, ε, was calculated as

$$\varepsilon = \frac{V_{\mathrm{tof}} - V_{\mathrm{ref}}}{V_{\mathrm{ref}}}. \tag{10}$$

The results are shown in Fig. 8. The ε distribution is less than 10 %, and the steam velocity can be obtained within a 10 % error regardless of the wetness fraction. However, the ensemble average of ε is 4.4 %, and V_{tof} tends to overestimate the actual steam flow rate even if the uncertainty of the determination of K in Fig. 6 is considered. Furthermore, ε tends to increase with the wetness fraction in each condition.



(a) P = 0.21 MPa

(b) P = 0.33 MPa

(c) P = 0.50 MPa

(d) P = 0.70 MPa

(e) P = 0.80 MPa

Fig. 7 Relationship between the reference and measured velocities in the wet steam flows.

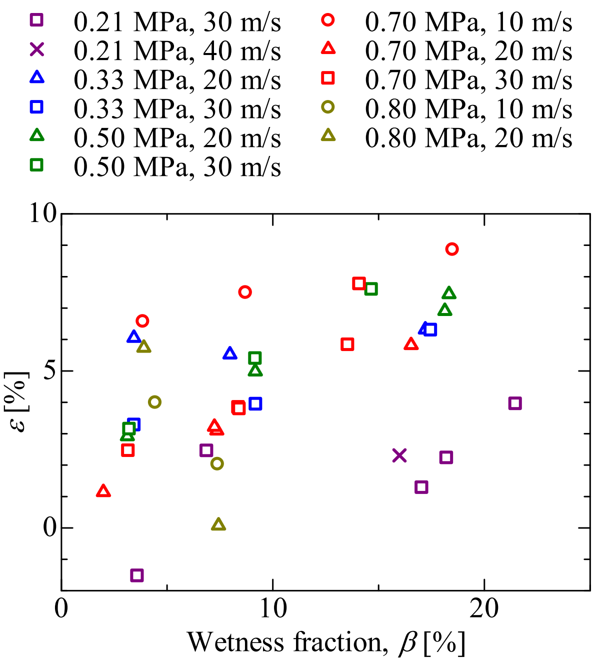


Fig. 8 Relationship between the measurement error ratio, ε, and wetness fraction, β.

4. Discussion

4.1 Change in speed of sound in wet steam

The speed of sound in wet steam, c_f, was required for deriving V_{tof} and was assumed to be the same as that in saturated steam at each pressure. However, the speed of sound in wet steam is not fully known [17–20], and determining its accurate value under experimental conditions is difficult. Furthermore, existence of a liquid film on the inside wall may disturb the ultrasonic propagation or change the propagation path resulting in a changed TOF. Thus, it is difficult to independently evaluate only the change in speed of sound due to the wetness. Therefore, all of these factors were evaluated as changes in the average speed of sound based on the TOF of ultrasound.

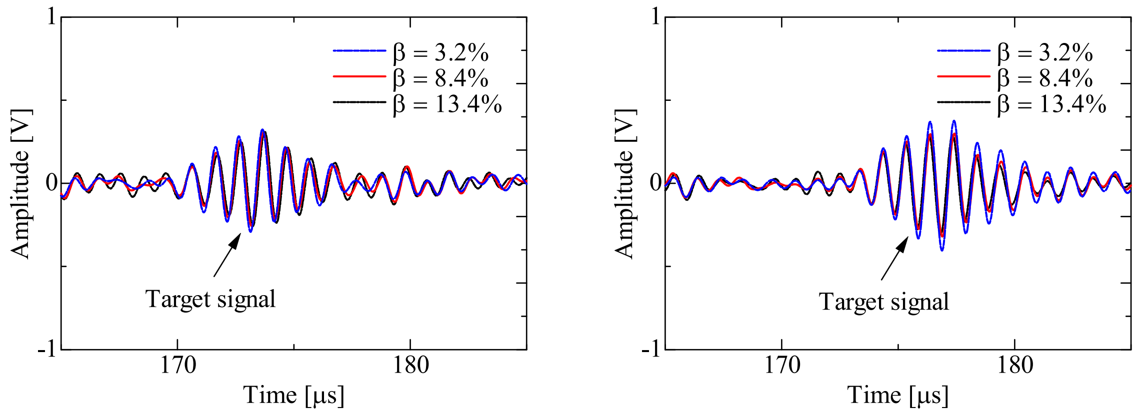
Fig. 9 represents the waveforms of the target signals at V_{ref} = 30 m/s at P = 0.70 MPa with different β in each direction. The transit times of the target signal from upstream to downstream, t_1, and from downstream to upstream, t_2, in each condition were slightly different. The TOF depends on the speed of sound and steam velocity. To evaluate the change in the speed of sound, the average of t_1 and t_2, t_{12}, was calculated as follows:

$$t_{12} = \frac{(t_1 + t_2)}{2} = \frac{D}{\cos\theta_2}\left(\frac{c_\mathrm{f}}{c_\mathrm{f}^2 - V_\mathrm{L}^2 \sin^2\theta_2}\right) + t_0. \quad (11)$$

Here, $c_\mathrm{f}^2 \gg V_\mathrm{L}^2 \sin^2\theta_2$, so

$$t_{12} \approx \frac{D}{c_\mathrm{f}\cos\theta_2} + t_0. \quad (12)$$

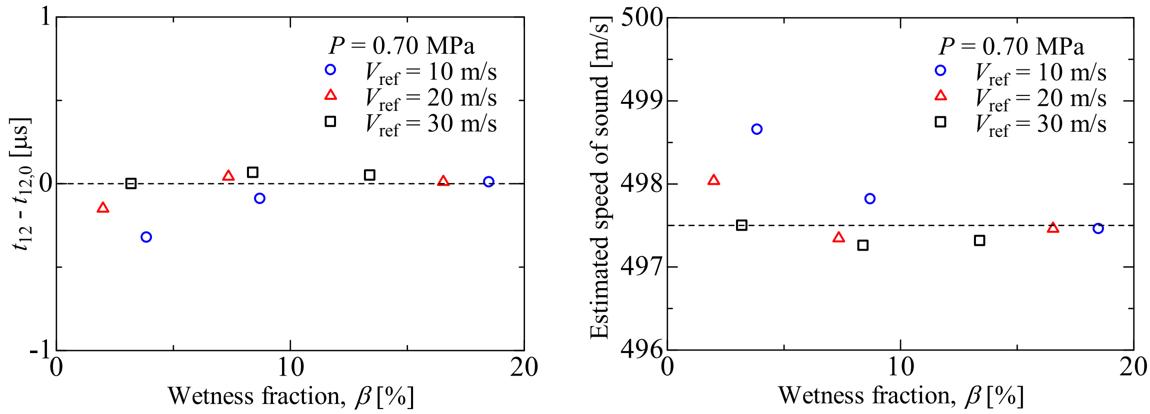
t_{12} at V_ref = 30.1 m/s, β = 3.2 % and P = 0.70 MPa were set as the standard conditions of $t_{12,0}$. To neglect t_0, $t_{12} - t_{12,0}$ was calculated, as shown in Fig. 10(a). Here, c_f as the standard condition was assumed to be 497.5 m/s, which is the speed of sound in saturated conditions. Based on $t_{12} - t_{12,0}$, the estimated speed of sound was calculated as shown in Fig. 10(b). In the same manner, the speed of sound in the superheated steam condition was calculated, as shown in Table 3. The variation in the speed of sound in wet steam from the standard condition is less than 1.2 m/s. Furthermore, the difference in the speed of sound between the reference and estimated values is less than 2.3 m/s in superheated steam. If the actual c_f in wet steam is 495.0 m/s at P = 0.70 MPa, then the difference in the speed of sound causes a measurement error ratio of 1.0%. This evaluation shows that the change in speed of sound and the effect of the liquid film on ultrasonic propagation in each condition were low, and these are not the main reason for the positive bias of the measurement error presented in Fig. 8.



(a) From upstream to downstream signal

(b) From downstream to upstream signal

Fig. 9 Comparison of the target signals in each wetness fraction at V_{ref} = 30 m/s and P = 0.70 MPa



(a) Relationship between $t_{12} - t_{12,0}$ and the wetness fraction

(b) Relationship between the estimated sound speed and wetness fraction

Fig. 10 Change in the transit time of the ultrasound and sound speed at P = 0.70 MPa with different wetness fractions and velocities on the basis of V_{ref} = 30.1 m/s at β = 3.2 %.

Table 3 Comparison of the reference and estimated speeds of sound in superheated steam at P = 0.71 MPa.

Steam temperature	Reference steam velocity, V_{ref}	Speed of sound (Reference [19])	Speed of sound (Estimated)
169.4 °C	9.8 m/s	501.2 m/s	498.6 m/s
174.7 °C	20.3 m/s	505.4 m/s	503.1 m/s
177.0 °C	30.5 m/s	507.1 m/s	506.4 m/s

4.2 Effect of volume fraction in the liquid phase

The flow regime can be estimated as a wavy flow or wavy to annular mist transition, as shown in Fig. 4. Fig. 11 shows a schematic of the flow regime in the pipe. With an increase in the wetness fraction, the cross-sectional liquid volume fraction increases, resulting in an increase in the average steam velocity in the cross-sectional area of the gas phase. This increase may cause an overestimation of V_{tof}. Xing et al. [16, 27] introduced a method to calculate the gas flow rate in two-phase flows from the flow rate measured using an ultrasonic flowmeter. They employed a slip flow model for stratified and annular flow regimes based on the Lockhart and Martinelli correlation [28] described as follows:

The cross-sectional void fraction, α, is described as

$$\alpha = \frac{1}{1 + \left(\frac{1-x}{x}\right)\left(\frac{\rho_{\mathrm{L}}}{\rho_{\mathrm{G}}}\right)S}, \tag{13}$$

where S is the slip ratio, which is the ratio between the mean gas and liquid velocities. The slip ratio is correlated as follows:

$$S = 0.28\left(\frac{1-x}{x}\right)^{-0.36}\left(\frac{\rho_{\mathrm{L}}}{\rho_{\mathrm{G}}}\right)^{-0.64}\left(\frac{\mu_{\mathrm{L}}}{\mu_{\mathrm{G}}}\right)^{0.07}. \tag{14}$$

In the calculation, saturated liquid and gas values at each pressure were used for ρ_{L}, ρ_{G}, μ_{L}, and μ_{G}. Considering the α, the corrected error ratio, $\varepsilon_{\mathrm{cor}}$, was calculated as

$$\varepsilon_{\mathrm{cor}} = \frac{\alpha V_{\mathrm{tof}} - V_{\mathrm{ref}}}{V_{\mathrm{ref}}}. \tag{15}$$

Figs. 12 show the calculated void fraction in each condition and the relationship between $\varepsilon_{\mathrm{cor}}$ and β. As the calculated void fraction was more than 98.8 %, considering the effect of volume fraction in the liquid phase does not substantially improve $\varepsilon_{\mathrm{cor}}$.

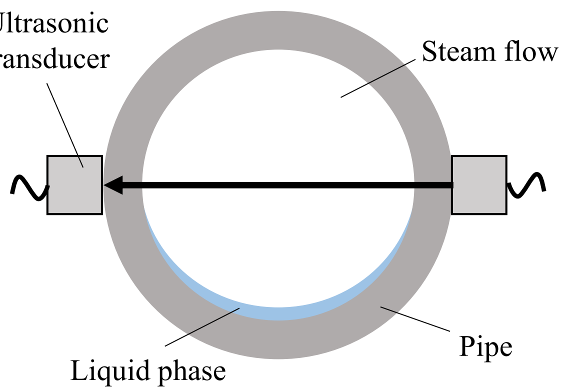
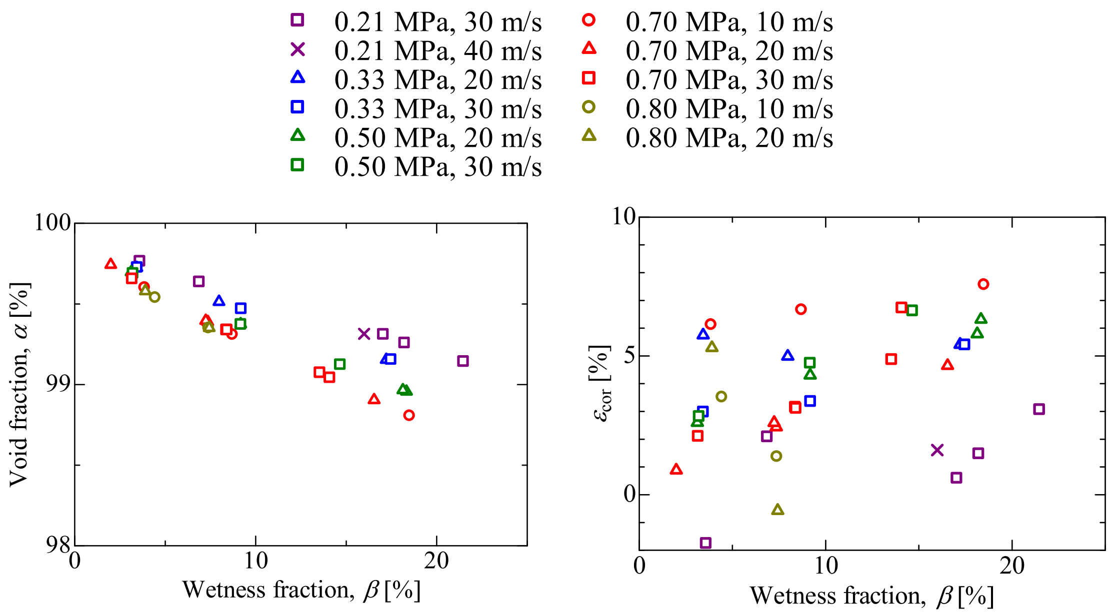


Fig. 11 Schematic of the test section in the stratified and wavy flows.



(a) Calculated void fraction in each condition.

(b) Relationship between the corrected error ratio, ε_{cor}, and wetness fraction, β.

Fig. 12 Effect of void fraction on the measurement error.

4.3 Change in the *K* factor

The change in the *K* factor due to the velocity distribution in wet steam flow was also considered in this study. As confirmed in Eq. (4), the accuracy of the *K* factor directly affects the measurement result of *V*. Numerous investigations have been performed for annular two-phase flows [29]. However, there have been a few experimental investigations regarding the velocity profile in the gas core in annular flows. Gill et al. [30] measured the velocity distributions in the gas core in an annular two-phase flow. With an increase in the water flow rate, the gas velocity at the pipe center increases, whereas it decreases near the pipe wall. Azzopardi and Teixeira [31, 32] measured the velocities in the gas core in an annular two-phase flow and showed that the values of *n* were smaller than the equivalent single-phase data values. It is considered that the velocity profiles in the superheated and wet steam conditions were different due to the liquid phase in our experiments. Fig. 13 shows the expected velocity profiles in the superheated and wet steam flow conditions under annular flow. The liquid film thickness is the same at the top and bottom walls. The velocity profiles in wet steam may change, and the velocity at the center in the pipe increases owing to the liquid film on the wall. Owing to the change in the velocity profile in the annular flow, the line-average velocity is larger than that in the superheated condition. As a result, the K factor determined based on the superheated or gas single-phase conditions is overestimated for measuring flow rates in the wet steam condition. In the horizontal pipe case, the liquid film at the bottom is thicker than that at the top wall. Thus, the velocity distribution may be vertically asymmetric and may change with the flow condition. However, the velocity distribution in the wavy flow changes due to the liquid film on the wall, and the K factor also increases. The change in K leads to a positive bias of V_{tof} in the wet steam condition, which is related to the flow regimes. Furthermore, K changes depending on the measurement line if the liquid phase exists. Therefore, determining K accurately under the wet steam condition becomes difficult. However, it is considered that this factor may not be neglected for measuring the flow rates in wet steam.

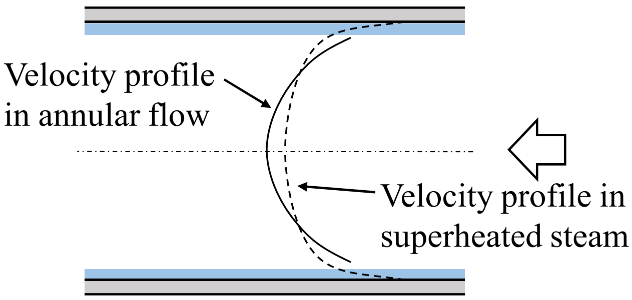


Fig. 13 Estimated velocity profiles in the superheated and wet steam flows.

5. Conclusions

In this study, flow rate measurements were performed in superheated and wet steam conditions with various pressure and wetness fractions using a laboratory-made clamp-on ultrasonic flow meter. The results were compared with those of a reference flowmeter.

At P = 0.21 MPa, determining the transit time difference between the ultrasonic signals transmitted from the upstream and downstream transducers was difficult because of the lower SNR. However, the SD method enabled the accurate determination of the flow rates. The flow rates in wet steam were determined at P = 0.2–0.8 MPa with $\beta < 20$ % within an error of 10 %, although the K factor was calibrated in superheated conditions and the speed of sound in the saturated condition at each pressure was employed. The error ratio of the flow rates tended to increase with the wetness fraction. Furthermore, the error ratio was biased toward positive values. The speed of sound in wet steam was evaluated using the measured transit time of ultrasound. The change in the speed of sound with the wetness fraction was insignificant, and the effect of speed of sound on the flow rate could be seen at less than 1 % of the flow rate. The effect of the liquid volume fraction on the flow rate measurement was evaluated based on the slip flow model. At most, 1.2 % of the flow rates was overestimated owing to the influence of the liquid volume fraction. The change in the velocity profile in the wet steam flow was discussed. The existence of the liquid phase on the pipe wall might change the velocity profile, resulting in increases in the line-average velocity and K factor. If K calibrated in the superheated condition is employed for flow rate measurements, then a change in K of wet steam leads to an overestimation of the flow rate.

In real situations at piping systems in industrial plants, the wetness fraction is typically unknown. Therefore, the measured flow rate using the clamp-on ultrasonic flowmeters may be overestimated by at most 10 %. Thus, steam should be supplied at a slightly higher flow rate than the requirement for satisfying the consumption of steam flow.

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Highlights:

- Measurements of steam flow rates in various wetness fractions were carried out.
- Standard deviation method enabled steam flow rate measurements at P = 0.21 MPa.
- Flow rate in wet steam can be obtained within 10 % error but was overestimated.
- Measurement error tended to increase with the steam quality.
- Factors of measurement errors in wet steam were evaluated.