Suitable Arrangement of UVP-lines for Tomographic Monitoring of Horizontal Gas-Liquid Two-Phase Pipe Flows

Yuichi Murai[1], Yuji Tasaka[1], and Yasushi Takeda[2]
[1] Faculty of Engineering, Hokkaido University, N13-W8, Kita-ku, Sapporo, 060-8628, Japan
[2] Swiss Federal Institute of Technology Zurich, Schmelzbergstrasse 9, 8092 Zurich, Switzerland
murai@ring-me.eng.hokudai.ac.jp

Gas-liquid interface that migrates along UVP measurement line can be detected as either the echo intensity or Doppler shift within ultrasound pulse. The principle is applied for development of void fraction profiler, which measures one-dimensional time-resolved void fraction profile along the measurement line. Upon the integration of the measurement principles, we designed an ultrasound Doppler based multiphase flowmeter. The flowmeter consists of tomographic interface detection realized by multiple UVP measurement lines within a pipe flow section in cooperation with liquid phase velocity profile measurement for flow rate estimation. In this paper, suitable arrangement of UVP-lines for tomographic monitoring of horizontal gas-liquid two-phase flows in a circular pipe is investigated and presented.

Keywords: Multiphase flow, gas-liquid two-phase flow, flow-metering, ultrasonic interfacial detection

1 INTRODUCTION

Use of ultrasound Doppler information for flow metering is known as non-invasive first-principle based measurement method[1]. Flow rate is simply given by area integration of the spatial distribution of velocity within a target plane. Since no calibration is required preliminarily, the target of flow can be expanded widely including multiphase flow. In this paper, we apply the ultrasonic Doppler method to gas-liquid two-phase pipe flows. Conventional approaches for flow metering in two-phase flow are such that phase distribution is sufficiently separated before flowing into the flow metering device, or is completely mixed to allow the approximation of homogeneous fluid[2]. By such an operation of flow prior to the measurement section, several flow metering principles for single-phase flow can be extendedly applied if adequate correction process is provided. For instance, Karman vortex flowmeter, Coriolis flowmeter, Venturi flowmeter, and turbine flowmeter are often applied. A common problem in these extensions of single-phase measurement technique to multiphase media is the necessity of tough calibration while a deviation much larger than the single-phase flow comes up due to inevitable unsteadiness of flow structure in multiphase system. Moreover, local changes of flow configuration for realizing the flow metering disturb heavily the multiphase conditions around them. The introduction of non-invasive sensing tools such as electric capacitance method and ultrasound method[3] to the measurement section, releases from these preliminary operations of multiphase flow. The ultrasound method consists of velocity profiling and interface detection since these two quantities in spatio-temporal domain give the componential flow rate in multiphase flow. The velocity profiling is established based on an existing instrument called ultrasound velocity profiler (UVP). UVP computes Doppler shift frequency of ultrasound pulse scattering from particles in fluid, and analyze the velocity distribution with repetitive process of the ultrasound pulses. The latter, i.e. interface detection by ultrasound, was developed by the authors [4]. Combination of these two quantities, which are obtained simultaneously from the ultrasound pulses, will provide the volumetric flow rate in multi-phase flow. The demonstration experiment shows that the present method is applicable to wide flow patterns of gas-liquid flow.

2 INTERFACE DETECTION

Gas-liquid interface in flowing state is measured by two kinds of information in echo signal of the ultrasound pulse reflected off the interface[4]. Fig. 1 shows the simplest case of the measurement configuration. We use a circular pipe of 40 mm in internal diameter.

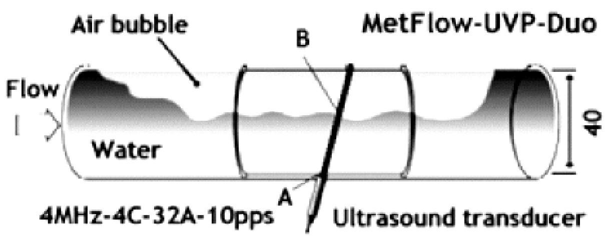


Fig. 1 UVP measurement line in a horizontal gas-liquid two-phase pipe flow

Fig. 2 shows a sample of instantaneous signal profiles for Doppler shift and echo intensity along the same measurement line. As the interface is perpendicular to the measurement line, the ultrasonic transducer receives strong echo intensity with which the interface position is measured. In contrast, no echo returns to the transducer when the interface inclines largely because of mirror reflection principle of ultrasound pulse. As the interface accompanies turbulent waves, echo recovers due to diffused reflection. Thus, interface detection from echo intensity signal works for highly turbulent slug flow.

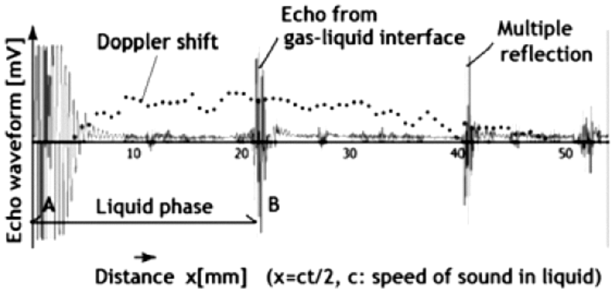


Fig. 2 Sample of instantaneous profiles of ultrasonic echo intensity and Doppler shift

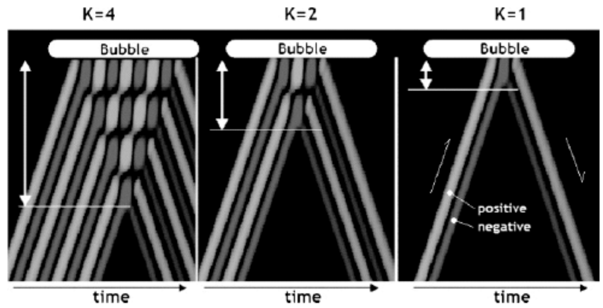


Fig. 3 Reflection of pulsed ultrasound on the gas–liquid interface. White and gray stripes stand for positive and negative local pressure, which forms the local standing wave near the interface as identified by the checker flag pattern.

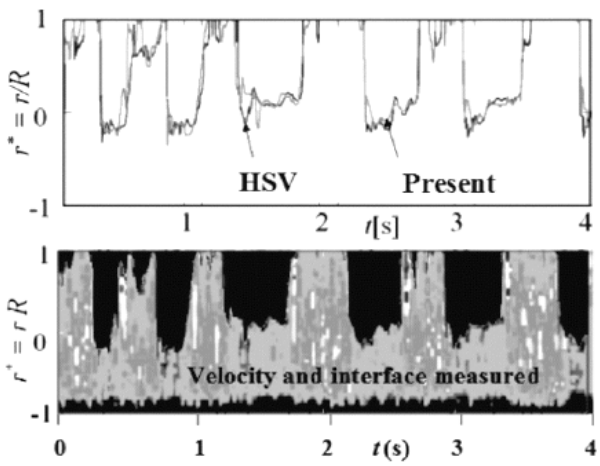


Fig. 4 Temporal fluctuation of the interface in slug flow regime: Top figure shows comparison between ultrasound (Present) and high-speed camera (HSV), bottom figure shows velocity distribution in liquid phase

Another source of information is Doppler shift profile along the measurement line. Fig. 3 shows how the local ultrasonic pulse interferences with its own reflected pulse in the vicinity of interface. Increasing of the cycle number in the pulse, standing wave emerges there so that Doppler shift disappears regardless to flow velocity. Thus, the interface can be detected by finding local null Doppler layer.

Fig. 4 shows a sample of interface in slug flow regime, measured by the combined algorithm of echo intensity and Doppler shift. The data agrees well with the data obtained by high-speed video camera taken from the side of the pipe.

3 TOMOGRAPHIC RECONSTRUCTION

A single UVP measurement line detects a single point of the interface along the path of ultrasound. It can be directly applied for axisymmetric two-phase pipe flow which consists of bubbles centered along the pipe axis. This condition is easily collapsed in horizontal two-phase pipe flow since gravity creates asymmetric interfacial structures. Fig. 5 shows overview of the present flow metering instrumentation for horizontal gas-liquid two phase flow[5]. The number of the measurement line (i.e. ultrasonic transducers) should be increased when the internal two-phase flow structure is complex.

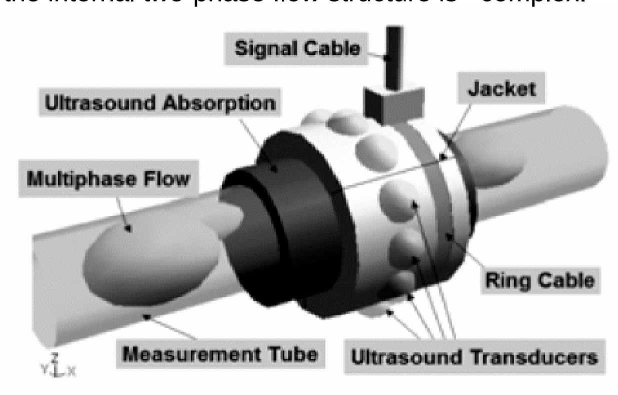


Fig. 5 Overview of ultrasonic multiphase flowmeter

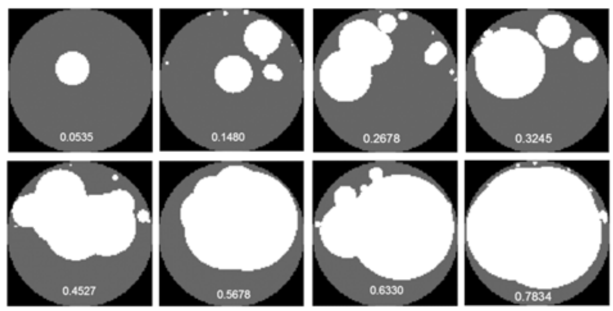


Fig. 6 Samples of synthetic void distributions in pipe cross section for numerical simulation of void fraction measurement

Fig. 6 shows several snapshot distributions of two phases in the pipe-cross section, which have been artificially generated inside a computer. The value in each figure indicates void fraction. We treat this value as true void fraction, and examine the void fraction measurement performance when a limited number of measurement lines are set in this domain. Here we assume that temporal resolution is sufficiently high in comparison with spatial one so that only spatial phase distribution is focused. Fig. 7 depicts six types of the measurement line arrangements. The term "one-way" means that transducers are set on one side while "two-way" means that a half of them confront another half of them. For the same number of transducers, interval distance of the measurement lines expands in the case of two-way arrangement.

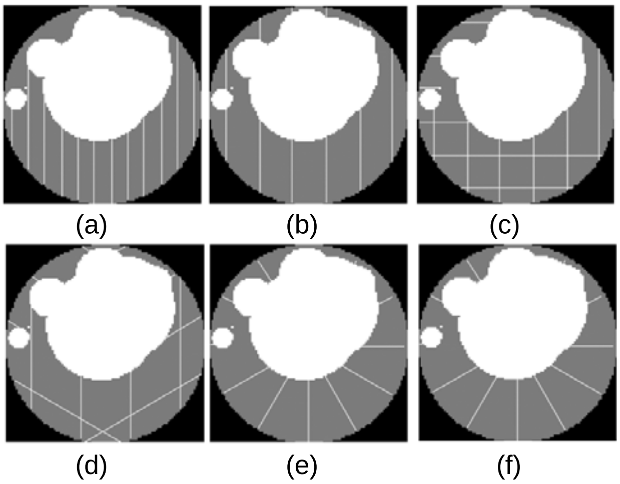


Fig. 7 Arrangement patterns of UVP measurement lines: (a) parallel one-way arrangement, (b) parallel two-way arrangement, (c) square grid arrangement, (d) triangular grid arrangement, (e) azimuthal one-way arrangement, and (f) azimuthal two-way arrangement.

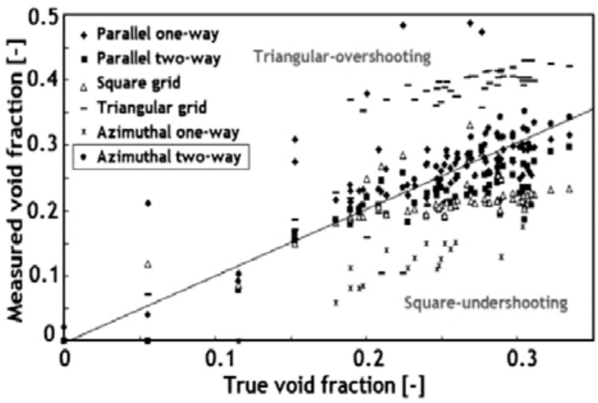


Fig. 8 Measurement performance of void fraction for six different arrangement patterns of UVP measurement lines.

Fig. 8 shows the relationship between true void fraction and measured void fraction. The plots are individual data for various combinations of gas-liquid interface given by numerical synthetic phase distribution in a circular cross section of a pipe as like in Fig.6. The plots in the vicinity of diagonal solid line are the condition with high accuracy. From the simulation, triangular grid arrangement always overshoots the measurement of void fraction. To the contrary, square grid arrangement undershoots the value. The best method of arrangement through out the entire condition is found to be azimuthal two-way arrangement. In the azimuthal two-way arrangement, the void fraction is computed from the interfacial position with the following equation.

$$\alpha_g = \frac{1}{\pi R^2}\left(\pi R^2 - \frac{1}{2}\int_0^{2\pi}\int_{R-h(\theta)}^{R} |r|\, dr d\theta\right) = 1 - \frac{1}{2\pi R^2}\int_0^{2\pi}\int_{R-h(\theta)}^{R} |r|\, dr d\theta \tag{1}$$

where α_g is void fraction averaged over the circular cross section of the pipe, R is the radius of the pipe, $h(\theta)$ is the thickness of liquid layer from the internal wall of the pipe in the radial inward direction as a function of azimuthal angle, r is the radial position variable and n is the number of measurement lines. The same equation in discrete form respect to the finite sampling of the interface in the azimuthal direction is written by

$$\begin{aligned} \alpha_g &= \frac{1}{2nR^2}\sum_{i=1}^{n}(A_i + B_i), \\ A_i &= |R - h(\theta_i + \pi)|\left(R - h(\theta_i + \pi)\right), \\ B_i &= |R - h(\theta_i)|\left(R - h(\theta_i)\right). \end{aligned} \tag{2}$$

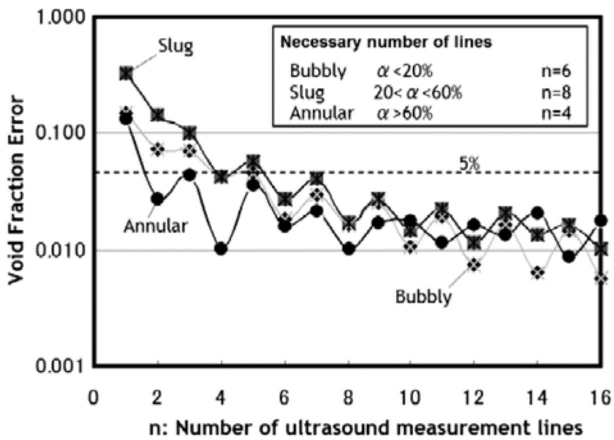


Fig. 9 Error converging performance of void fraction with increase in the number of UVP measurement lines classified in three regimes

Fig. 9 is the simulation data by which we can discuss how the number of measurement lines, n, should be determined. In the data, all the conditions are classified into three groups regarding the range of void fraction so that the trend's difference is investigated by the regime; bubbly flow, slug flow, and annular flow. At n=1, i.e. only a single measurement line in the vertical direction is set, the error level is higher than 10% in any flow regime. Annular flow, which has a liquid contact layer on the inner wall and a large gas phase inside, is judged to be the easiest two-phase flow pattern since a less number of measurement lines is allowed to reduce the error. The initial error of slug flow is high, but the error can be reduced as the number increases enough. Bubbly flow is placed between these two. In any pattern, use of even number for the measurement lines always provides better accuracy than odd number. This is explained by the fact that the spatial occupation of gas phase is correctly identified when two interfaces along the diameter are detected. Giving a threshold at 5 % error in void fraction, we conclude that six measurement lines are necessary for bubbly flow regime, eight for slug flow regime, and four for annular flow regime. Here, it is worth noting that these conditions are for instantaneous void fraction measurement, but not for mean value. The error for the mean void fraction is much less than the data presented here because there is ignorable bias error for the azimuthal two-way arrangement.

Fig. 10 shows three-dimensional shapes of the gas phase in slug flow regime, which is measured in real two-phase flow by CT technique [5]. We have carried out the same set of measurement simulation while the data are omitted in this paper.

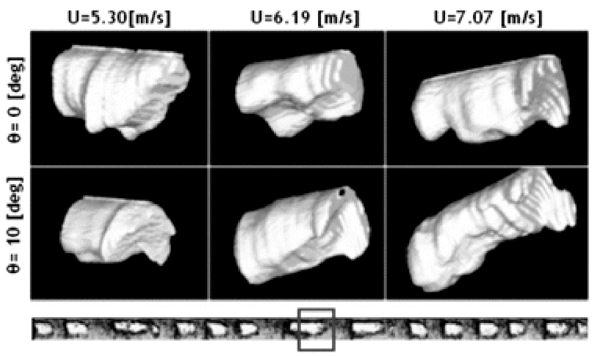


Fig. 10 3-D shapes of gas phase in slug flow regime measured by optical backlight CT and applied for examining UVP-based void fraction measurement.

4 LIQUID FLOW RATE MEASUREMENT

By areal integration of the liquid velocity distribution within the pipe cross section, instantaneous liquid volume flow rate has been measured successfully as shown in Fig. 11. Remarkable fluctuation in the data shows intermittent passage of liquid slugs in the pipe. From this data, not only the mean flow rate but also fluctuating flow rate can be evaluated both for the amplitude and frequency, i.e, power spectrum. Fig. 12 shows comparison of mean liquid flow rate measured by UVP with the data of direct volume measurement method. Error level is restricted within 5 %.

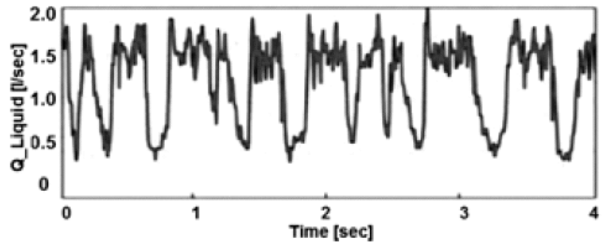
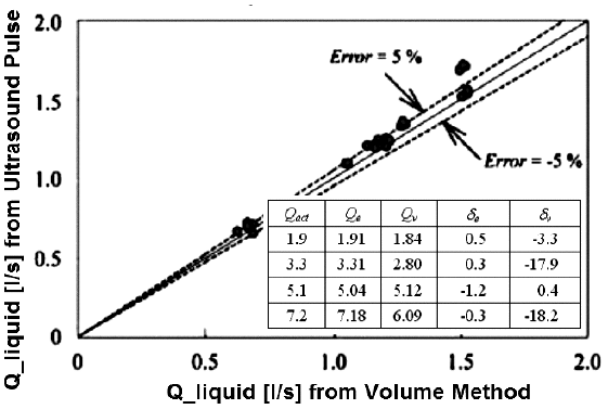


Fig. 11 Fluctuation of liquid volume flow rate in slug flow regime measured by UVP with parallel one-way arrangement.



Q_{act}	Q_e	Q_v	δ_e	δ_v
1.9	1.91	1.84	0.5	-3.3
3.3	3.31	2.80	0.3	-17.9
5.1	5.04	5.12	-1.2	0.4
7.2	7.18	6.09	-0.3	-18.2

Fig. 12 Flowmetering accuracy for liquid volume flow rate

5 CONCLUDING REMARKS

Gas-liquid two-phase flow in a horizontal pipe is measured by UVP. In the present study, we investigated the dependence of void fraction measurement performance on spatial arrangement method of UVP-lines. Numerical simulation concluded that “azimuthal two-way” (see Fig. 7(f)) worked the best. The method has been applied to liquid flowmetering successfully.

REFERENCES

[1] Takeda Y, Velocity profile measurement by ultrasonic Doppler shift method, Int. J. Heat and Fluid Flow, 7 (1986), 313-318.

[2] Oddie G, Pearson RA, Flow-rate measurement in two-phase flow, Annu. Rev. Fluid Mech. 36 (2004), 149-172.

[3] Murakawa H, Kikura H, Aritomi M, Application of ultrasonic Doppler method for bubbly flow measurement using two ultrasonic frequencies, Exp. Thermal Fluid Sci., 29 (2005), 843-850.

[4] Murai Y, Tasaka Y, Nambu Y, Takeda Y, Gonzalez SR, Ultrasonic detection of moving interfaces in gas-liquid two-phase flow, Flow Meas. Instr., 21(2010), 356-366.

[5] Murai,Y, Inaba K, Takeda Y., Yamamoto, F., Backlight imaging tomography for slug flows in straight and helical tubes, Flow Meas. Instr., 18 (2007), 223-229.

[6] Takeda Y, Murai Y, Tasaka Y, Ultrasonic multiphase flowmeter, ultrasonic multiphase flow rate measurement program, and multiphase flow rate measurement method using ultrasonic wave, US Patent, No. US8,401,805 B2 (2013)