MEASUREMENT SYSTEM OF TWO-PHASE FLOW USING ULTRASONIC VELOCITY PROFILE MONITOR

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1. INTRODUCTION

It is one of the most important problem in two-phase flow dynamics to clarify its multi-dimensional flow characteristics. Measurement methods of multi-dimensional characteristics in two-phase flow are classified into two types; contact and non-contact. The contact type sensor such as an electric probe is inserted in a flow and thus disturbs it, so that the measurement accuracy is still not satisfactory. There are measurement methods based on ultrasonic, capacitance, conductance, optics and radiation in non-contact type methods. Laser Doppler Anemometry based on an optical technique is excellent particularly in space and time resolution. This method requires a long time for measuring a spatial distribution of flow characteristics in a channel. Recently, an ultrasonic Doppler method for velocity profile measurement has been developed for liquid flow measurements by Takeda (1995). It has been approved that this method is a powerful tool in flow measurement. It can measure a local velocity instantaneously as a component in the ultrasonic beam direction, so that a velocity field can be measured in space and time domain.

In this work, a measurement system using an Ultrasonic Velocity Profile Monitor (UVP) has been developed, which can measure simultaneously the multi-dimensional flow characteristics of bubbly flow such as velocity profiles of both gas and liquid phases, a void fraction profile and a turbulent intensity profile. The present measurement system is applied to a countercurrent bubbly flow in a vertical rectangular channel to verify its capability.

2. EXPERIMENTAL APPARATUS

The experimental apparatus was composed of a water circulation system, an air supply system, a test section and a measurement system. Air and water were used as working fluids. The test section was a vertical rectangular channel of 10mmx100mmx700mm made of Plexiglas as shown in **Fig.1**. The measurement system consisted of the UVP and a personal computer to record and treat data. Water was fed into the upper tank and flowed downward in the test section. Micro particles of nylon powder were suspended in water to reflect ultrasonic pulses. The air supply system consisted of a compressor and a pressure regulation valve. Bubbles were injected from five needles located near the bottom of the test section.

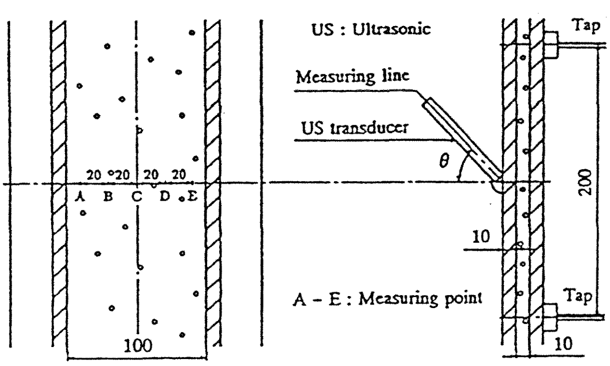


Fig.1 Test section

An ultrasonic transducer was installed on the outside surface of the front wall of the channel with a contact angle, θ, and a gap between the transducer and the wall was filled with a jelly to prevent a reflection of ultrasonic pulses on the wall surface. The hydrostatic head was simultaneously measured as a pressure drop between the pressure taps installed on the side wall using a differential pressure transducer to get an averaged void fraction.

3. MEASUREMENT PRINCIPLE

The working principle of the UVP is to use the echo of ultrasonic pulses reflected by micro particles suspended in the fluid. An ultrasonic transducer takes roles of both emitting ultrasonic pulses and receiving the echoes, that is, the backscattered ultrasound is received for a time interval between two emissions.

The position information, x, is obtained from the time lapse, τ, from the emission to the reception of the echo:

$$x = c\tau / 2 \tag{1}$$

where c is a sound speed in the fluid. An instantaneous local velocity, $u(x_i)$, as a component in the ultrasonic beam direction, is derived from the instantaneous Doppler shift frequency, f_D, in the echo:

$$u_{UVP} = cf_D / 2f \tag{2}$$

where f is the basic ultrasonic frequency. The UVP specification used in this work is tabulated in **Table 1**.

Table 1 The specification of the Ultrasonic Velocity Profile Monitor

Basic ultrasonic frequency	4MHz
Maximum measurable depth	758mm(variable)
Minimum spatial resolution	0.74mm
Maximum measurable velocity	0.75m/s(variable)
Velocity resolution	0.75mm/s(variable)
Measurement points	128
The number of profiles	1,024

Since the sound speed of the longitudinal wave is the most fundamental parameter for this method, it is not possible to treat a two-phase medium as a homogeneous single phase medium, because a sound wave experiences multiple reflection among bubbles and its path returning to the transducer cannot be straight. It is however possible to obtain velocity profiles of liquid phase until the position of the nearest bubble from the transducer. Therefore, the authors attempted to derive information from each individual profiles by analyzing their shapes. 9,216 (1,024x9) velocity profiles per one experimental condition were collected to treat them statistically.

The position and velocity in the ultrasonic beam direction were converted into the horizontal position, y, and axial velocity $u(y)$, respectively by considering the contact angle of the transducer to the wall.

A profile of the probability of data existence, $P_s(y)$ is defined as a ratio of the number of data receiving the echo to the number of total profiles. A probability density function, $P_u(y,u)$, includes the velocity information of both phases. Assuming that each probability density function of both phases can be expressed by a normal distribution,

$$N[\bar{u}, \sigma^2](u) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{(u-\bar{u})^2}{2\sigma^2}\right], \tag{3}$$

the probability density function of mixture velocity is given by

$$\begin{aligned} P_u(y,u) &= \varepsilon(y) N[\bar{u}_G(y), \sigma_G^2(y)](u) \\ &+ (1-\varepsilon(y)) N[\bar{u}_L(y), \sigma_L^2(y)](u) \,. \end{aligned} \tag{4}$$

where $\bar{u}_G$, $\bar{u}_L$, σ_G and σ_L are average velocities and standard deviations of both phases respectively, $\varepsilon(y)$ is the probability of bubble existence. These five variables are calculated numerically and iteratively by the least squares method.

Since the ultrasonic pulse is reflected at the interface as long as a bubble exists, the bubble velocity can be always detected as an interface velocity. On the other hand, the ultrasonic wave is not reflected in water if a micro particle does not exist therein. As a result, water velocity is not always measured in the profile. Therefore, it is necessary to revise the probability of bubble existence as follows:

$$\kappa(y) = P_s(y)\,\varepsilon(y) \tag{5}$$

where $\kappa(y)$ is called the probability of bubble data existence in this work.

An example of the probability density function obtained from the UVP data is representatively shown in **Fig.2**. It is difficult to derive the genuine information under high void fraction conditions because the multiple reflection of an ultrasonic pulse is induced by bubbles. In addition, very little information on bubble velocities can be obtained at very low void fractions. To solve these problems, several data processing programs were developed in this work in order to eliminate wrong data induced by a multiple reflection under conditions of high void fraction and to select only the profiles including bubble velocities under conditions of very low void fractions. These programs were based on the fact that positive velocity data means bubble upflow velocity and negative velocity data does water downward one because of countercurrent bubbly flows dealt with in this work.

It is clarified that the both $\bar{u}_g$ and $\bar{u}_l$ in the probability density function velocity does not change even if the original data are treated with these program. Therefore, they were used only to get $\bar{u}_g$ and σ_g in the probability density function of bubble velocity. **Figure 2** demonstrates a comparison of a typical probability density function of mixture velocities calculated by the above-mentioned procedure with experimental results.

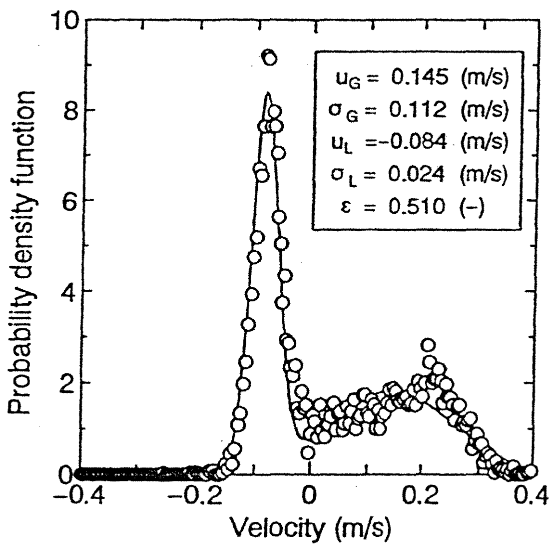
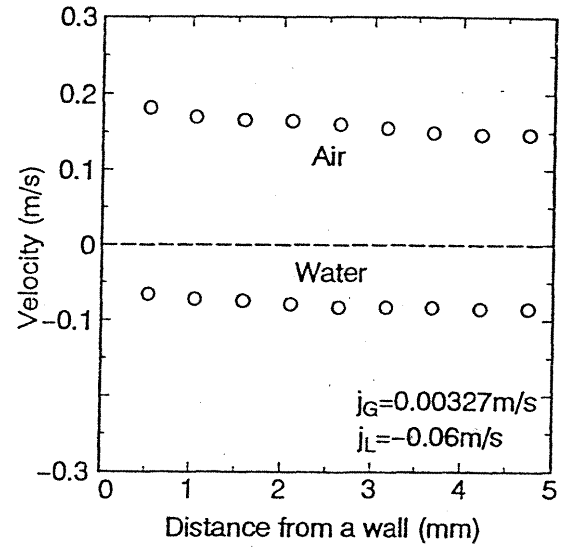


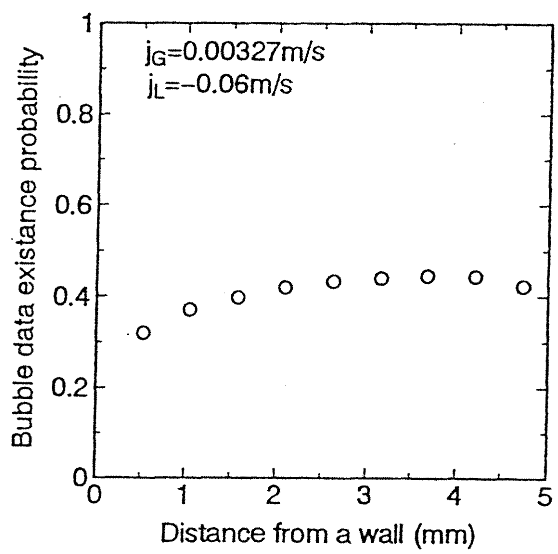
Fig.2 Typical probability density function

4. MEASURED RESULTS

The developed measurement system was applied to countercurrent bubbly flows channel. **Figure 3 (a)** and **(b)** shows measurements of velocity profiles in both phases and a probability profile of bubble data existence. Velocities of both phases are not zero on the wall because the ultrasonic pulse is emitted at an angle with respect to the channel wall and its diameter of 5mm, which thus induces meaningful error of velocity measurements near the wall. However, this uncertainty is not a feature for two-phase flow measurement but appears for the velocity profiles measured for a single phase flow with the UVP.



(a) Velocity profiles in both phases



(b) Probability profile of bubble data existence

Fig.3 Measured flow characteristics

The probability of bubble data existence means that a bubble exists in an ultrasonic pulse path when the pulse is emitted, and is closely related to the void fraction. The bubble size, position and configuration cannot be known directly from UVP measurements. It is supposed that the bubble size and configuration are at random and that they are statistically uniform at the whole points in the channel. Assuming that the local void fraction is proportional to the local probability of bubble data existence and that the proportional constant (the conversion factor), k, is uniform in the channel since it is dependent on bubble size and configuration, the average void fraction is expressed by

$$<\alpha> = k\int_A \kappa \, dA \, / \, A = k<\kappa> \, . \quad (6)$$

Since the average void fraction was obtained by measuring the hydrostatic head, the conversion factor, k, was calculated by substituting measured average void fraction, $<\alpha>$, and average probability of bubble existence, $<\kappa>$ into Eq.(6). Then, local void fraction, $\alpha(y)$, is given by

$$\alpha(y) = k\kappa(y). \quad (7)$$

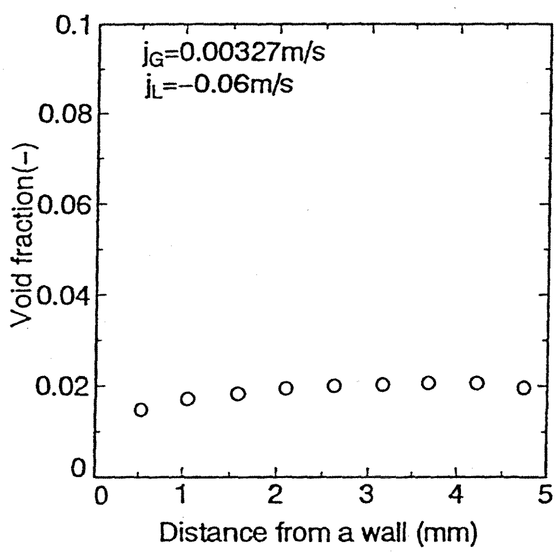


Fig.4 A typical void fraction profile

Figure 4 shows a typical void fraction profile obtained by this method. Furthermore, the average volumetric flux of bubble, $<j_G>$, is

$$<j_G> = \frac{\int_A \alpha u_G \, dA}{A} = \frac{k\int_A \kappa u_G \, dA}{A}. \quad (8)$$

The conversion factor can also be calculated by substituting $\kappa(y)$ and $u_G(y)$ obtained by experiments and $<j_G>$ given from the experimental condition into Eq.(8). The accuracy of the average void fraction evaluated by this procedure is within 20% error.

In this work, turbulent intensity is defined as a standard deviation of water velocity fluctuation which is a continuous phase, σ_L. The standard deviation profile in the channel can be calculated from Eq.(2). Typical results of a water single flow and a countercurrent bubbly flow are shown in **Fig.5**. Local velocities were however measured not at a point but on the area because of an ultrasonic beam diameter of 5mm, so that the absolute value of the standard deviation in a water phase is not significant. Hence, the standard deviation ratio of a countercurrent bubbly flow to a water single phase flow is selected as two-phase multiplier of turbulent intensity, $\sigma_{LTPF}/\sigma_{LSPF}$ in this work. The results are also shown in **Fig.5**. In general, turbulent intensity in a bubbly flow is larger than that in liquid single phase flow because bubbles agitate the flow. It can be seen from the figure that $\sigma_{LTPF}/\sigma_{LSPF}$ is larger than unit and that the two-phase multiplier of turbulent intensity becomes larger with going toward the center of the channel.

REFERENCE

Takeda, Y., Velocity Profile Measurement by Ultrasonic Doppler Method, *Experimental Thermal and Fluid Sci.*, **10** (1995) 444–453.

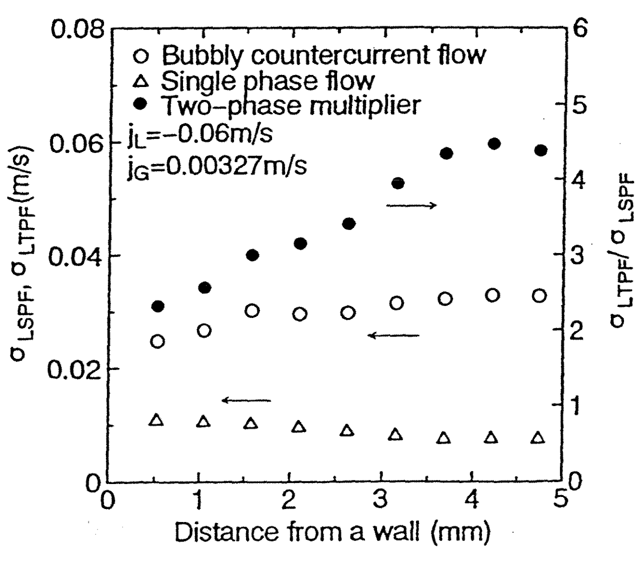


Fig.5 Turbulence intensity