MULTI-DIMENSIONAL FLOW CHARACTERISTICS OF COUNTERCURRENT BUBBLY FLOW, (II) EFFECTS OF AIR AND WATER FLOW RATES

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1. INTRODUCTION

It is one of the most important subjects in the research of two-phase flow dynamics to clarify its multi-dimensional flow characteristics. Therefore, the authors have developed a new measurement system which is composed of an Ultrasonic Velocity Profile Monitor (UVP) (Aritomi et al., 1996) in order to clarify the multi-dimensional flow characteristics in countercurrent bubbly flows and to offer a data base to validate numerical codes for multi-dimensional two-phase flow. The ultrasonic Doppler method for velocity profile measurement has been developed for liquid flows by Takeda (1995). It has been approved that this method is a powerful tool in flow measurement in the following ways: It can measure a velocity profile instantaneously so that velocity field can be measured in space and time domain.

In this paper, the proposed measurement system was applied to fully developed countercurrent bubbly flows in a vertical rectangular channel in order to verify its capability. At first, both bubble and water velocity profiles and void fraction profiles in the channel were investigated statistically under various conditions of both gas and liquid phase flow rates. Next, a two-phase multiplier profile of turbulent intensity in the channel was discussed as a ratio of the standard deviation of velocity fluctuation in a countercurrent bubbly flow to that in a water single phase flow. Finally, concerning the drift flux model, the distribution parameter and the drift flux are calculated directly from these profiles.

2. EXPERIMENTAL APPARATUS

Figure 1 shows a schematic diagram of an experimental apparatus. Air and water were used as working fluids. The experimental apparatus was composed of a water circulation system, an air supply system, a test section and a measurement system. The test section was a vertical rectangular channel of 10mmx100mm x700mm made of Plexiglas. The measurement system consisted of the UVP and a personal computer to record and treat data.

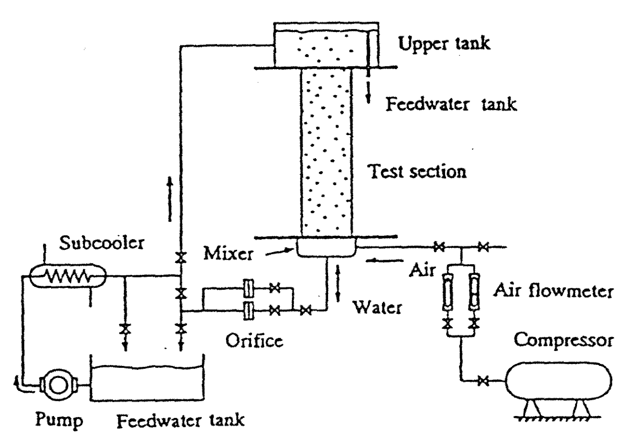


Fig.1 A schematic diagram of experimental apparatus

An ultrasonic transducer was installed on the outside surface of the front wall of the channel with a contact angle of 45° 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. After both air and water flow rates were set up at the desired values, 9,216 (1,024x9) velocity profiles along a measured line were measured under one experimental condition to treat them statistically. 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. The experimental conditions are tabulated in **Table.1**.

Table 1 Experimental conditions

System pressure	Atmospheric pressure
Water specific velocity	−0.06, −0.12m/s
Air specific velocity	0.00195 – 0.00418m/s

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. The position information is obtained from the time lapse from the emission to the reception of the echo and a sound speed in the fluid. An instantaneous local velocity as a component in the ultrasonic beam direction is derived from the instantaneous Doppler shift frequency in the echo. Horizontal position and axial velocity can be obtained by considering the contact angle of the transducer to the wall.

A probability density function includes the velocity information of both phases. Assuming that each probability density function of both phases can be expressed by a normal distribution,

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

the probability density function of mixture velocity is given by

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

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

As long as a bubble exists, the ultrasonic pulse is reflected at its surface. Therefore, the bubble velocity can be always detected as the interfacial velocity. On the other hand, the ultrasonic wave is not reflected in water where a micro particle does not exist. 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:

$$\kappa(y) = P_s(y)\ \varepsilon(y) \quad (3)$$

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

The average void fraction was obtained by measuring the hydrostatic head. Assuming that the local void fraction is proportional to the local probability of bubble data existence and that the proportional constant, k, is uniform in the channel since it is dependent on bubble size and configuration, the average void fraction is expressed by

$$<\alpha> = k\int_A \kappa\ dA\ /\ A = k<\kappa>\ . \quad (4)$$

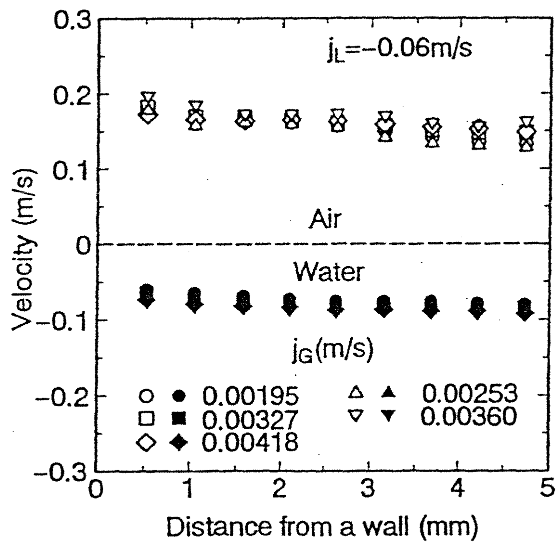
The proportional constant, k, was calculated from measured average void fraction, $<\alpha>$, and measured average probability of bubble existence, $<\kappa>$. Then, local void fraction, $\alpha(y)$, is given by

$$\alpha(y) = k\,\kappa(y). \quad (5)$$

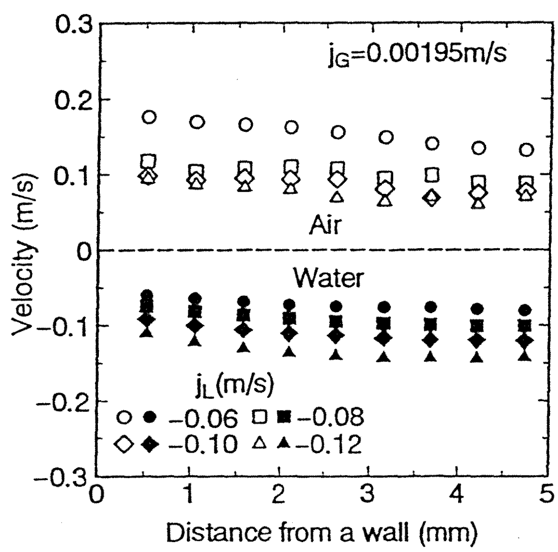
3. RESULTS AND DISCUSSION

Velocity profiles of both phases in the channel were measured with the UVP. The typical experimental results, which were measured under the condition of a constant water flow rate and various air flow rates, are shown in **Fig.2 (a)**. Since it is very difficult to measure the velocities near the wall with significant accuracy due to an ultrasonic beam diameter of 5mm, they are omitted in the figure. Water velocities becomes higher toward the center of the channel from the wall in the same tendency as water single phase flow. In contrast with this, bubble velocities are higher near the wall than those in the core. The flow characteristics of a countercurrent bubbly flow is strongly dependent on the water velocity which is a continuous phase and a bubble rising velocity is induced by the difference between the buoyancy and interfacial drag force. Since air flow rates are much lower than water ones under the present conditions, the velocity profiles of both phases are scarcely varied even if an air flow rate increases. **Figure 2 (b)** shows the experimental results of velocity profiles of both phases at a constant air flow rate and in reference to water flow rates. It can be seen from the figure that water velocities becomes higher but their profiles are scarcely influenced with a change in a water flow rate.

Figure 3 (a) and **(b)** show the typical experimental results of void fraction profile in reference to air flow rates and water flow rates, respectively. It can be seen from these figures that void fraction profiles are almost flat in countercurrent bubbly flows. Since air flow rates are much lower than water ones under the present experimental conditions, water velocity profiles are scarcely varied even with a change in air flow rates and bubble velocity is dependent on the water velocity profiles. The void fraction, therefore, increases with an increase in air flow rates as shown in **Fig.3 (a)**. Moreover, as the water flow rate increases, the bubble rising velocity is decreased, so that void fraction becomes larger as shown in **Fig.3(b)**.

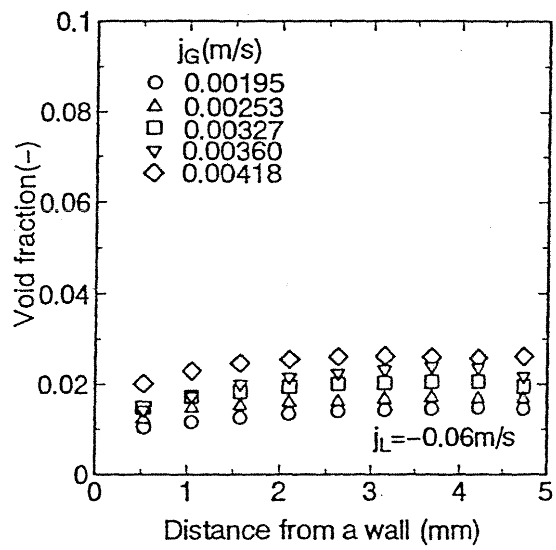


(a) Effect of air flow rates

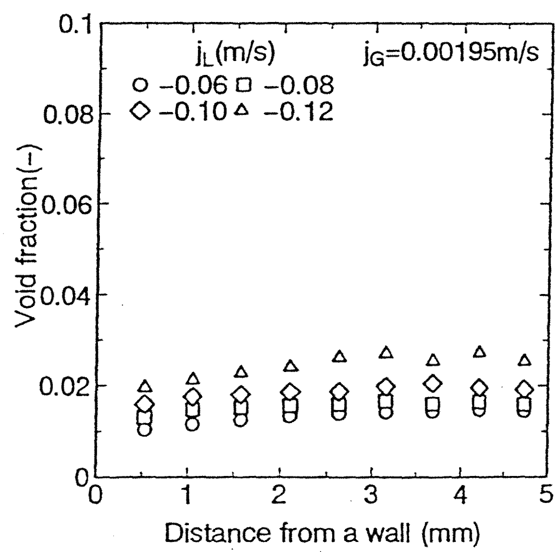


(b) Effect of water flow rates

Fig.2 Typical velocity profiles of both phases



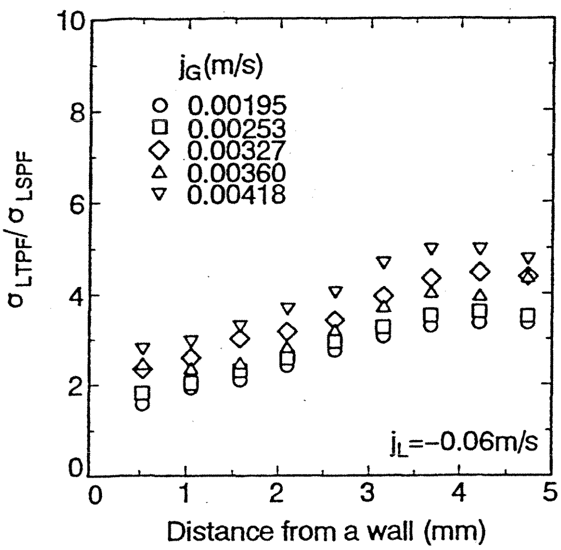
(a) Effect of air flow rates



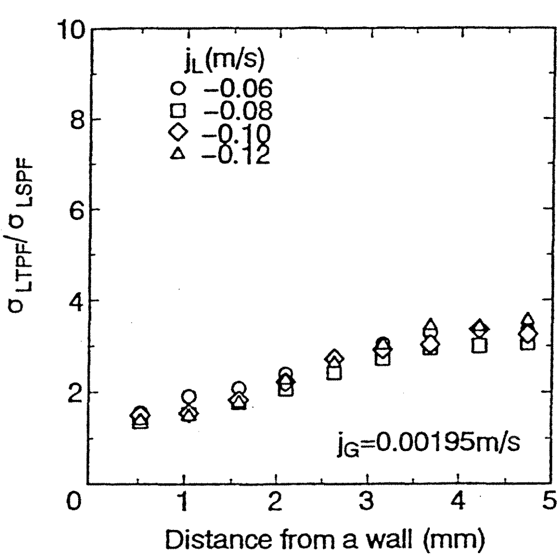
(b) Effect of water flow rates

Fig.3 Void fraction profiles

As a general rule, turbulent intensity in a bubbly flow is larger than that in liquid single phase flow because bubbles agitate the flow. 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).



(a) Effect of air flow rates



(b) Effect of water flow rates
Fig.4 Turbulent intensity profiles in countercurrent bubbly flow

Since local velocities were measured not at a point but on the area because of an ultrasonic beam diameter of 5mm, 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 water single phase flow is selected as two-phase multiplier of turbulent intensity, $\sigma_{LTPF}/\sigma_{LSPF}$. **Figures 4 (a)** and **(b)** show the typical experimental results of the two-phase multiplier of turbulent intensity in reference to air flow rates and water flow rates, respectively. The two-phase multiplier of turbulent intensity becomes larger with going toward the center of the channel. It can be seen from the figures that $\sigma_{LTPF}/\sigma_{LSPF}$ is enhanced with increases in air or water flow rates.

The drift flux model proposed by Zuber and Findley (1965) is applied widely to two-phase analysis codes. The drift flux, V_{gj}, and the distribution parameter, C_0, in the drift flux model can be calculated by

$$V_{gj} = \int_A (u_G - j)\, dA/A \tag{6}$$

and

$$C_0 = \frac{\int_A \alpha j dA/A}{\int_A \alpha dA/A \cdot \int_A j dA/A} \tag{7}$$

where j is volumetric flux. In this work, the drift flux and the distribution parameters were calculated by substituting the measured velocity profiles of both phases and void fraction profiles in to Eqs.(6) and (7), respectively. It can be seen from **Fig.3 (a)** and **(b)** that a void fraction profiles are almost flat. Consequently, the distribution parameter is almost 1.0. Substituting properties of air and water into the correlation proposed by Zuber and Findley (1965), V_{gj} = *0.231m/s*. The experimental results are identical to this value.

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