Pergamon

0301-9322(93)E0033-2

Int. J. Multiphase Flow Vol. 20, No. 4, pp. 753–762, 1994

0301-9322/94 $7.00 + 0.00

SIMULTANEOUS MEASUREMENT OF LIQUID AND BUBBLE VELOCITIES IN A CYLINDRICAL BATH SUBJECT TO CENTRIC BOTTOM GAS INJECTION

M. IGUCHI[1], T. KONDOH[2†] and T. UEMURA[3]

[1]Department of Materials Science and Processing, Faculty of Engineering, Osaka University, 2-1 Yamadaoka, Suita, Osaka, 565 Japan

[2]Graduate School, Osaka University, Japan

[3]Department of Industrial Engineering, Faculty of Engineering, Kansai University, 3-3-35 Yamate, Suita, Osaka, 564 Japan

(Received 20 July 1993; in revised form 22 December 1993)

Abstract—A vertical bubbling jet was generated in a cylindrical bath by injecting air from a single-hole centric nozzle. The axial and radial velocity components of bubble and liquid in the vertical bubbling jet were measured simultaneously using an electro-resistivity probe and a two-dimensional laser Doppler velocimeter. The output signal of the LDV was processed on a personal computer at a sampling frequency of 2 kHz. Hold signals were eliminated. Discrimination of the bubble and liquid velocities was made by referring to the output signal of the electro-resistivity probe. The accuracy of the present velocity measurement of bubbles and liquid was found to be satisfactory from a comparison with results obtained using an image processing technique for high-speed video pictures, a laser void meter or a two-dimensional electro-resistivity probe.

Key Words: air–water bubbling jet, velocity measurement, LDV, electro-resistivity probe

1. INTRODUCTION

Knowledge of bubble and liquid velocities is required for better understanding of transport phenomena in gas–liquid two-phase flow systems. Bubble rising velocity can be measured using a two-element electro-resistivity probe (Castillejos & Brimacombe 1987; Iguchi *et al.* 1991), while it is well known that a laser Doppler velocimeter is the most suitable device for measuring liquid velocity of transparent fluid flow. However, output signals of LDV applied to gas–liquid two-phase flow involve both bubble and liquid velocities, and thus discrimination of the two velocities is of essential importance. The bubble velocity is defined as the interfacial velocity.

Sheng & Irons (1991) review previous methods of separating bubble and liquid velocities and point out that the methods fall into the following three main categories:

(1) Discrimination based on the signal wave form. For example, Durst & Zare (1975), Boerner *et al.* (1984), Tsuji & Morikawa (1982).
(2) Discrimination based on the signal analysis and light blocking. For example, Lee & Sreenivasan (1982), Ohba *et al.* (1986), Durst *et al.* (1986)
(3) Discrimination based on the velocity probability distribution function. For example, Marie & Lance (1983).

Furthermore, Sheng & Irons (1991) conclude that these three techniques cannot separate the bubble and liquid velocities at high gas holdup and for large, irregular bubbles and propose a method of permitting the separation using a one-dimensional laser Doppler velocimeter (LDV) and an electro-resistivity probe (EP). This system can distinguish only the vertical velocity signals of liquid and bubbles. However, under high gas holdup conditions, bubbles usually rise along zig-zag paths (Iguchi *et al.* 1993), so that the vertical and horizontal velocities of the bubbles and liquid should be measured.

In the present study a method of discriminating the vertical and horizontal velocity signals of bubble and liquid is developed using a two-dimensional LDV system and a single-element

†Now with Sumitomo Metal Industries, Japan.

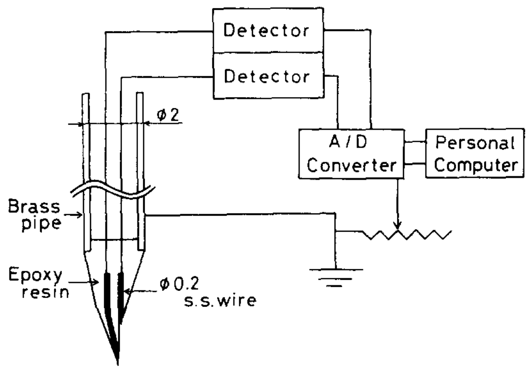

Figure 1. Schematic of the two-element electro-resistivity probe.

electro-resistivity probe after Sheng & Irons (1991). The adequacy of the system is checked for an air–water vertical bubbling jet using a two-element electro-resistivity probe, a laser void meter and an image processing technique for high-speed video pictures.

2. EXPERIMENTAL APPARATUS AND MEASURING METHOD

2.1. Electro-resistivity probe (EP)

Gas holdup ϵ, bubble frequency f_B, mean bubble rising velocity $\bar{u}_B$ and mean chord length $\bar{L}_B$ are measured using a two-element electro-resistivity probe (Iguchi *et al.* 1991, 1992). The gas holdup is determined as the ratio of the sum of bubble passing time at the probe tip to the total measuring time, and bubble frequency is defined as the number of bubbles passing through the probe tip during 1 s.

A schematic of the measuring system is shown in figure 1. The output signal of the EP is A/D converted and then processed on a personal computer at a maximum sampling frequency of 10 kHz. The vertical and horizontal distances between the two probe tips (L_P and L_H) are 2.5 and 0.5 mm, respectively. The rising velocity of a bubble is determined by dividing L_P by the travelling time of the bubble from the lower tip to the upper one. Since bubbles rise along zig-zag paths due to highly turbulent liquid motion, reliable velocity measurement of a bubble smaller than L_P is difficult. Therefore the rising velocity measurement of bubbles of diameters less than 3 mm is practically impossible. It should be noted that all measurements described here and below are made on the centerline of the vessel.

2.2. Laser Doppler velocimeter (LDV)

A schematic of the two-dimensional argon ion laser Doppler velocimeter system is shown in figure 2. Alumina (Al_2O_3) powder of 1 μm diameter is used as the seeding particle. Only when a new signal is detected by the LDV, is that signal stored and processed on a personal computer

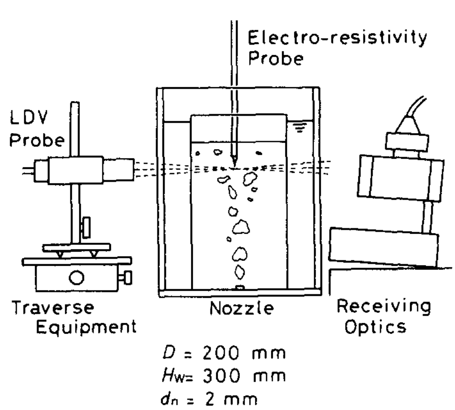

Figure 2. Schematic of the two-dimensional LDV system.

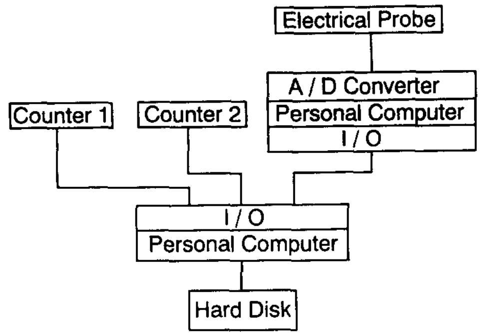

Figure 3. Outline of the data processing system

and thus the so-called hold signal is eliminated. It is well known that the forward scattering configuration is superior to the backward scattering configuration. Nevertheless, the latter is used in many cases. Accordingly we employed the two configurations to investigate the difference between the results obtained with them under the same experimental conditions.

The outline of the data processing system is shown in figure 3. This system (Laser: Coherent, Innova 70; FIV system: Kanomax, System 8832) was originally developed for measuring three velocity components, i.e. axial, radial and tangential, simultaneously and hence it has three counters. In each LDV negative velocities are detected using a shifter (TSI LDV Processor 1980B). The third counter processes the output signal of the electro-resistivity probe as if it were a velocity signal, which is used to discriminate the bubble and liquid velocities.

2.3. Image processing measurement of bubble rising velocity

Bubble rising velocity u_B is determined by applying an image processing technique to side view pictures of bubbles taken by a high-speed video camera at 200 frames/s. Examples of the shape of rising bubbles are shown in figure 4, where z is the distance from the nozzle exit, D is the bath diameter, H_w is the bath depth, d_n is the inner diameter of nozzle and Q_G is the air flow rate. The migration distance of the center of a bubble is divided by migration time to give u_B. The details of the technique are reported elsewhere (Uemura *et al.* 1990; Iguchi *et al.* 1993).

The present image processing method can measure the rising velocity of a bubble larger than approx. 1 mm. This method was solely employed to check the validity of the LDV/EP method. Since the EP cannot detect precisely the rising velocity of bubbles smaller than 3 mm, bubbles generated due to disintegration of larger bubbles are removed in this analysis. These smaller bubbles play a minor role in inducing the upward rising liquid flow.

2.4. Discrimination of liquid and bubble velocities using an electro-resistivity probe and a two-dimensional LDV system

A single-element electro-resistivity probe (EP) is placed just above the intersection point of four laser beams, i.e. the control volume as shown in figure 5, though it is placed just below the control volume in the measurement of Sheng & Irons (1991). The probe position employed by Sheng & Irons is likely to disturb the flow. The distance from the center of the control volume

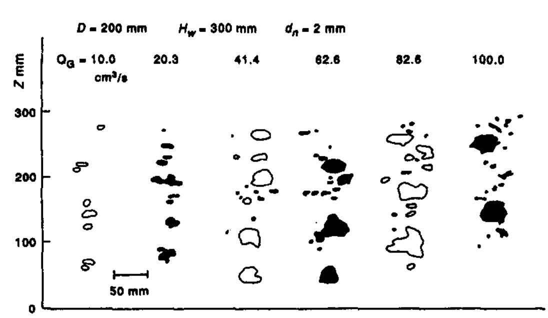

Figure 4. Bubbles visualized with a high-speed video camera.

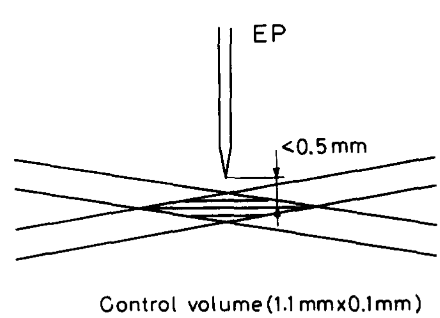

Figure 5. Relation between EP position and control volume.

to the electrode tip is less than 0.5 mm. The time resolution, therefore, is approx. 1 ms under the present experimental conditions.

The output signal of the EP is employed to judge whether the output signal of the LDV originates from bubbles or liquid. The EP signal drops from the voltage of liquid level to the voltage of bubble level at the arrival of a bubble and then rises back to the liquid level voltage after the passage of the bubble. The threshold value for detecting the arrival and departure of a bubble is set to be the mean of the voltages of the liquid and bubble levels.

It should be noted that it takes approx. 1 ms for a bubble to be detected by the EP after it has passed through the control volume. In order to examine the effect of this time delay on the discriminated result,the time during which every bubble was passing through the electrode tip was shifted by 1 ms into the past on a personal computer and the discrimination was made in a preliminary measurement. The result almost agreed with the original one without the time shift. This is probably because bubbles have an irregular and non-spherical shape.

Therefore, a more sophisticated conditional sampling method should be developed for the measurement of liquid velocity around a bubble in the bubbling jet.

Only results based on the discrimination without the time shift will be shown below. Figure 6 shows the LDV and EP signals obtained in the forward-scattering configuration. The threshold value of the EP signal is 2.1 V. That is, LDV signals obtained for an EP signal greater than 2.1 V are regarded as a liquid signal. When the EP signal is smaller than 2.1 V, the LDV signals are regarded as a bubble signal. This discrimination method is practically impossible for bubbles of diameter less than approx. 3 mm.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Comparison between gas holdup data obtained using the present LDV/EP system and two-element EP system

Figure 7 was drawn to check the validity of the present newly developed LDV/EP system shown in figure 3. It is demonstrated that the gas holdup values measured by the present LDV/EP system and two-element EP system agreed well with each other. This fact partly indicates that the present LDV/EP system is reasonable.

3.2. Number of bubble and liquid signals

Figure 8 compares the number of liquid signals with the bubble signals obtained during 10 min in the forward-scattering configuration. In this case the data rate is about 300 Hz at $z = 175$ and 195 mm, but it is considerably smaller at $z = 30$ mm. The number of bubble signals is less than 30% of that of liquid signals even for $\epsilon = 60\%$. On the other hand, the backward-scattering experiment reveals that the latter is almost identical with the former for $\epsilon = 60\%$ near the nozzle exit (figure 9). The data rate in the backward-scattering configuration is approximately one order of magnitude smaller than that in the forward-scattering configuration, though the numbers of

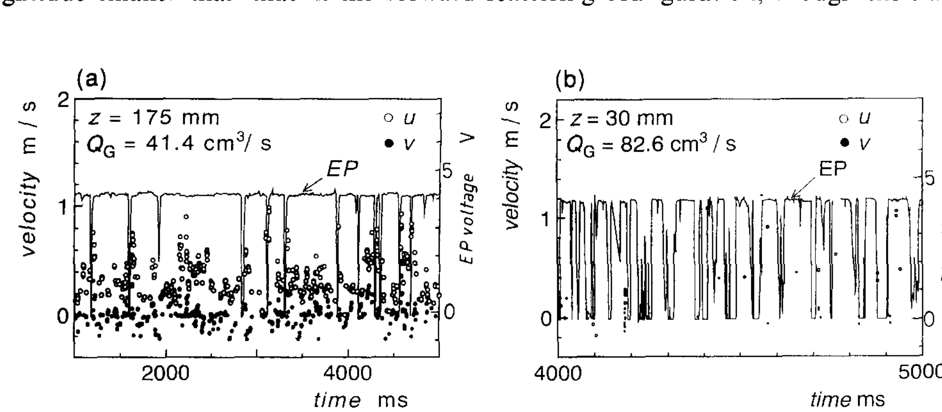

Figure 6. (a) Example of LDV and EP signals ($d_n = 2$ mm, $z = 175$ mm, $Q_G = 41.4\ cm^3/s$). (b) Example of LDV and EP signals ($d_n = 2$ mm, $z = 30$ mm, $Q_G = 82.6\ cm^3/s$).

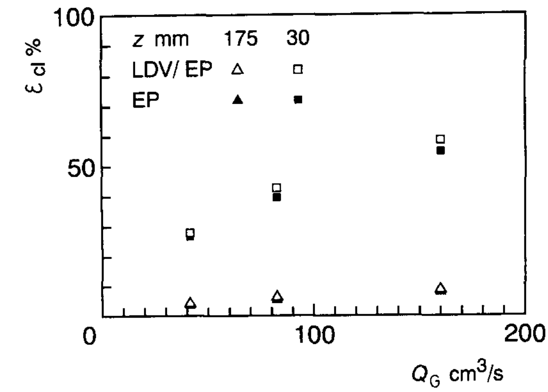

Figure 7. Gas holdup data obtained using LDV/EP and EP systems.

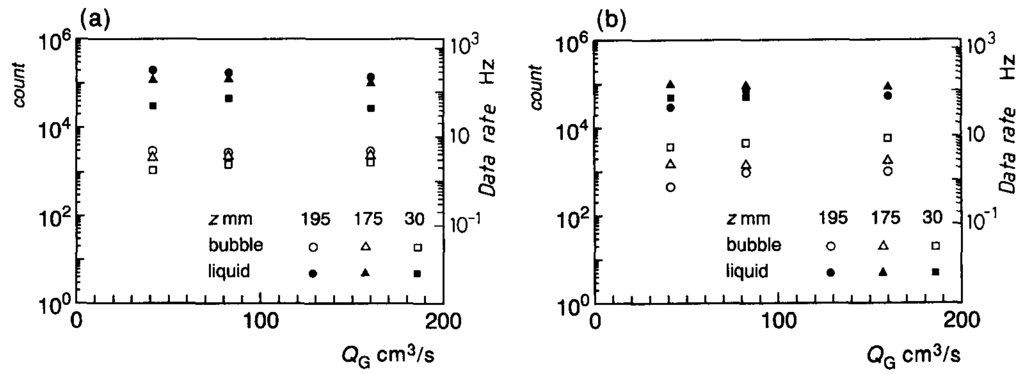

Figure 8. (a) Number of bubble and liquid signals of the axial velocity component obtained in forward-scattering configuration. (b) Number of bubble and liquid signals of the radial velocity component obtained in forward-scattering configuration.

bubble signals are almost the same for the two configurations. Accordingly the backward-scattering configuration is superior for the purpose discriminating bubble signals from liquid ones.

3.3. Comparison of probability distribution functions between bubble and liquid velocities

Figure 10 shows the probability distribution functions of the bubble and liquid velocities obtained using the present LDV/EP system in the forward-scattering configuration. Data of a velocity less than -0.4 m/s are not shown here to save space. The probability distribution function of the axial bubble velocity has two peaks. The higher peak is closely related to the larger bubbles generated at the nozzle exit. The lower peak, around $u_B = 0$, might be produced by downward

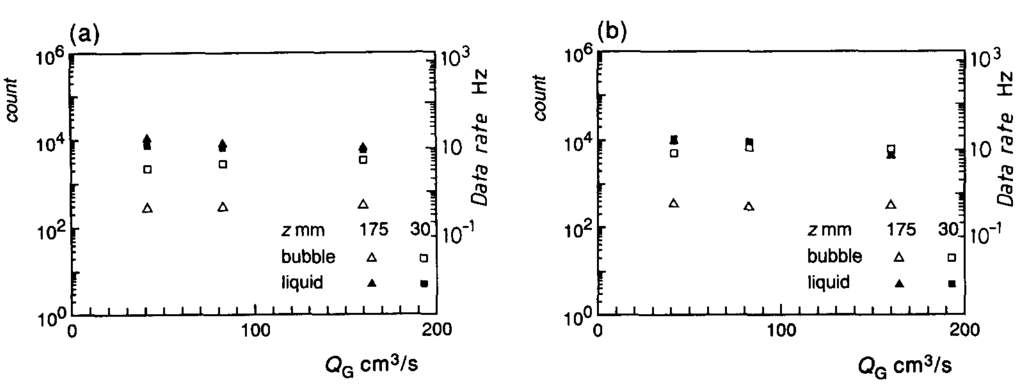

Figure 9. (a) Number of bubble and liquid signals of the axial velocity component obtained in backward-scattering configuration. (b) Number of bubble and liquid signals of radial velocity component obtained in backward-scattering configuration.

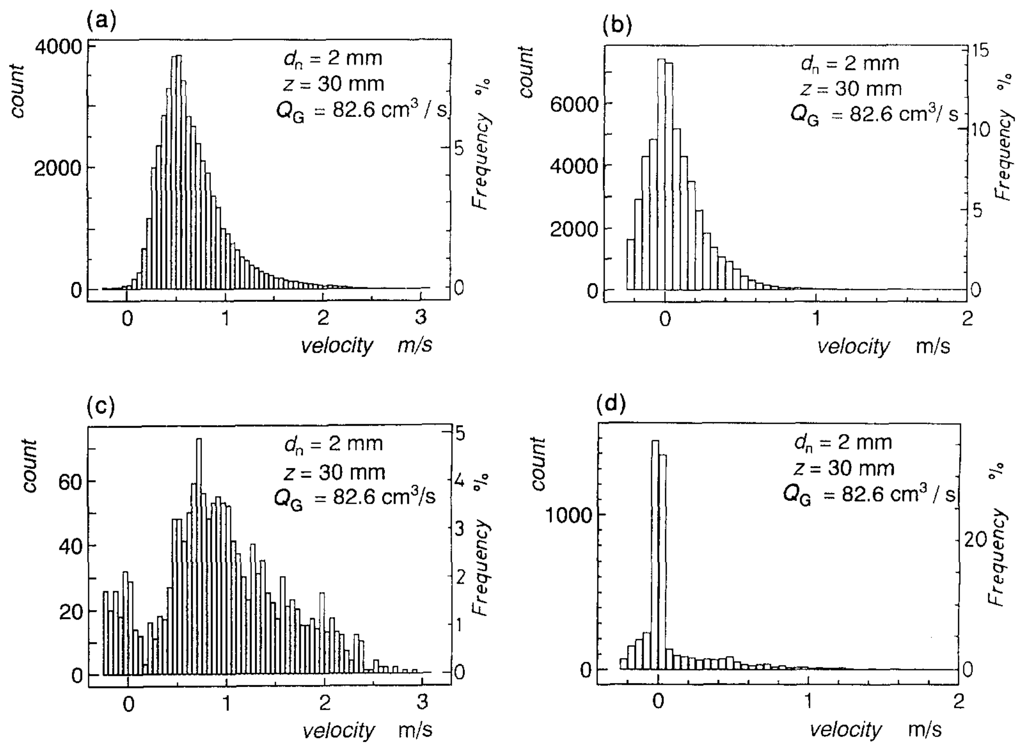

Figure 10. (a) Probability distribution function of axial liquid velocity. (b) Probability distribution function of radial liquid velocity. (c) Probability distribution function of axial bubble velocity. (d) Probability distribution function of radial bubble velocity.

moving smaller bubbles entrained in the wake of larger bubbles. Anyway, the existence of a negative axial bubble velocity is somewhat strange, because the EP was originally designed to detect upward rising bubbles.

A similar peak around $u_B = 0$ can be seen on the probability distribution function obtained using a laser void meter (see figure 11). No negative value, however, exists in figure 11. Explanation of the negative value of the axial bubble velocity observed here must be left for future study.

Meanwhile, both probability distribution functions of the axial and radial liquid velocities have their respective single peak. It is clear that the distributions of the radial liquid and bubble velocities are almost symmetrical with respect to zero. Such symmetrical distributions are reasonable because the measurement is made on the centerline ($r = 0$) of the vessel.

The mean values and the root mean square values of the axial and radial velocity components are shown against gas flow rate in figure 12. The difference between the axial mean velocities

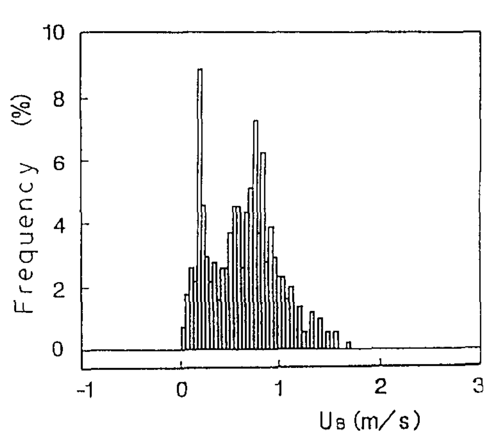

Figure 11. Probability distribution function obtained using a laser void meter.

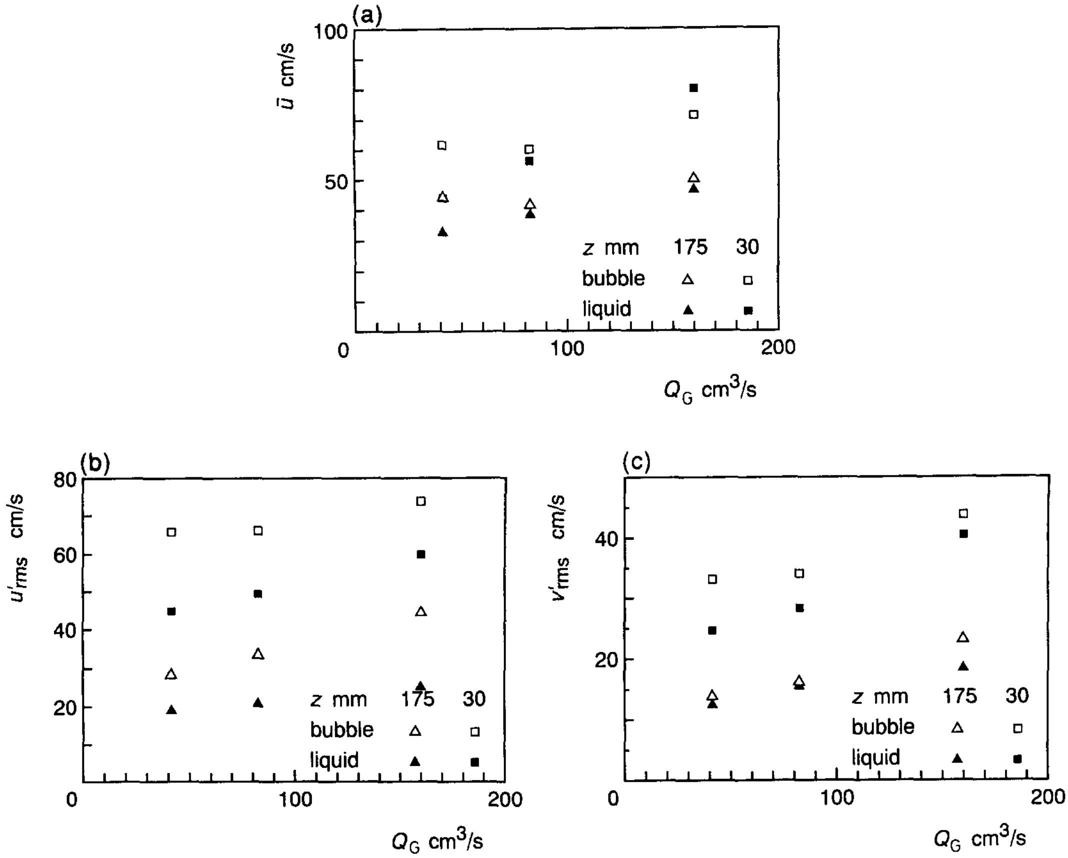

Figure 12. (a) The mean values of axial bubble and liquid velocities. (b) The RMS values of axial bubble and liquid velocities. (c) The RMS values of radial bubble and liquid velocities.

(rising velocity) of the bubble and liquid, i.e. the so-called relative velocity (average mean velocity difference), becomes small as the gas flow rate increases at an axial position far from the nozzle ($z = 175$ mm), but near the nozzle ($z = 30$ mm) it changes in a somewhat complicated manner. The RMS value of the axial bubble velocity is much greater than that of liquid. The same is true for the radial velocity component. This is attributable to the fact that the probability distribution function of bubbles spreads more widely than that of liquid as shown in figure 10.

3.4. Comparison of liquid velocity with raw velocity before discrimination

From a practical point of view, it is of major importance to make clear under what conditions the mean and RMS values of liquid velocity can be approximated by their respective values of raw velocity involving both the contribution of liquid and bubble velocities. The above-mentioned velocity data suggest that such a situation is established in the forward-scattering configuration. Figures 13 and 14 demonstrate that the mean and RMS values of liquid velocity can be well approximated by their respective values of raw velocity in the forward-scattering configuration. Also, the same result is obtained in the whole axial region except near the nozzle exit ($z = 30$ mm) even if the backward-scattering configuration is used.

3.5. Comparison among bubble rising velocities based on three different measurement methods

In figure 15 the mean bubble rising velocity data against gas flow rate are shown, determined using the LDV/EP system, a two-element electro-resistivity probe system or an image processing system (IP). The measured values of $\bar{u}_B$ varied around the mean value within a scatter of $\pm 15\%$. However, it should be noted again that these methods cannot detect the velocity of bubbles of diameters nearly equal to or less than 3 mm.

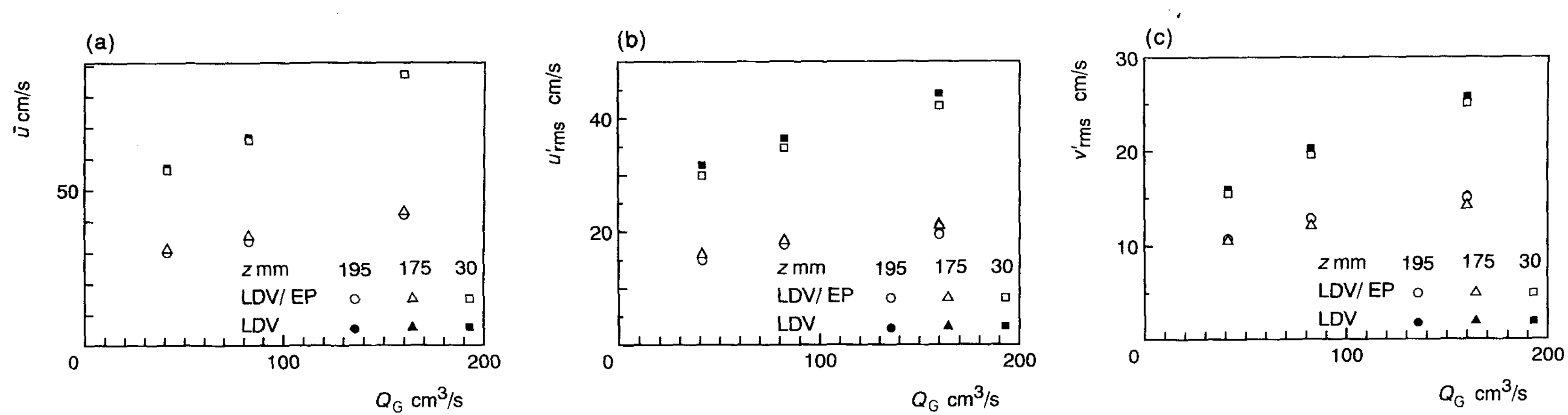

Figure 13. (a) Liquid velocity and raw velocity in forward-scattering configuration (mean values of axial velocity component). (b) Liquid velocity and raw velocity in forward-scattering configuration (RMS values of axial velocity component). (c) Liquid velocity and raw velocity in forward-scattering configuration (RMS values of radial velocity component).

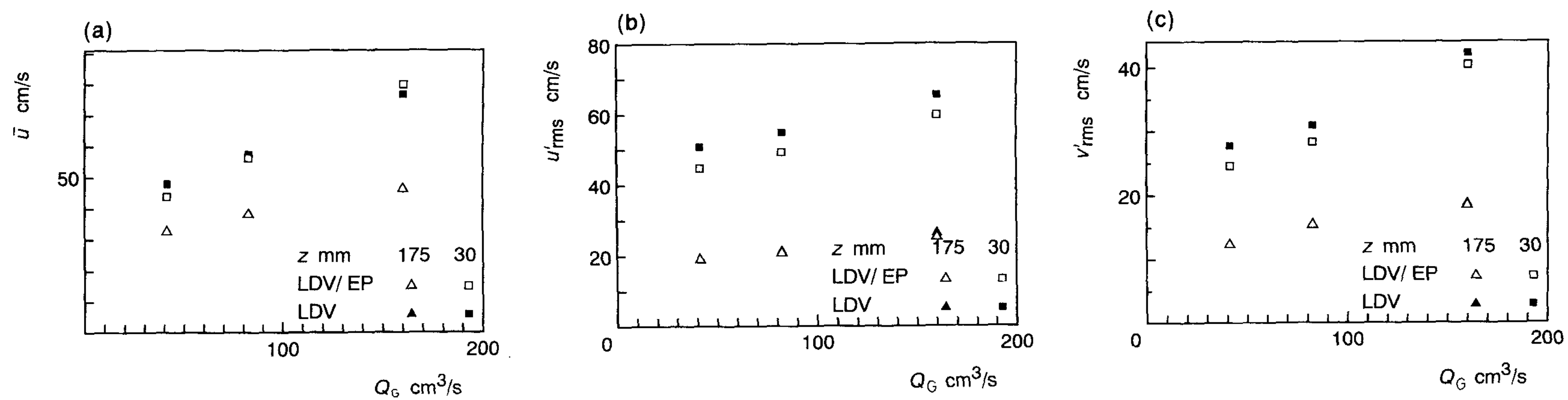

Figure 14. (a) Liquid velocity and raw velocity in backward-scattering configuration (mean values of axial velocity component). (b) Liquid velocity and raw velocity in backward-scattering configuration (RMS values of axial velocity component). (c) Liquid velocity and raw velocity in backward-scattering configuration (RMS values of radial velocity component).

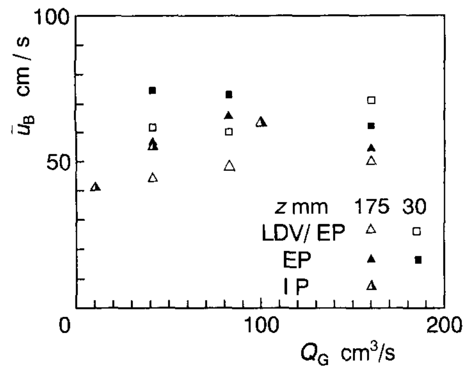

Figure 15. Relation between mean bubble velocity and gas flow rate.

4. CONCLUSIONS

The method of discriminating the bubble and liquid velocities was developed using a two-dimensional LDV and a single-element electro-resistivity probe. Measurements were performed in the forward- and backward-scattering configurations on the centerline of a cylindrical bath subject to centric bottom gas injection. The results are summarized as follows.

(1) This system is applicable to bubbling jets having a bubble diameter nearly equal to or larger than 3 mm. The ratio of the number of bubble velocity data to that of liquid velocity data is less than 30% in the forward-scattering configuration even if the gas holdup is about 60%. Consequently, the mean and RMS values of liquid velocity agree well with their respective values of raw velocity involving both the contribution of liquid and bubble. This ratio is, however, strongly dependent on the gas holdup ϵ in the backward-scattering configuration; about 100% at $\epsilon = 60$ and 10% at $\epsilon = 15\%$. At $\epsilon = 60\%$ liquid velocity cannot be approximated by the raw velocity before discrimination in the backward-scattering configuration.

(2) The probability distribution function of the axial bubble velocity has two peaks, whereas that of the axial liquid velocity has a single peak. The bubble rising velocity determined by the present LDV/EP method agrees well with that obtained using a two-element electro-resistivity probe or an image processing technique for high-speed video pictures, showing the adequacy of the present discrimination method.

(3) The so-called mean relative velocity (average mean velocity difference) between bubble and liquid was found to become small with an increase in gas flow rate at an axial position far from the nozzle exit under the present experimental conditions.

REFERENCES

Boerner, T., Martin, W. W. & Leutheusser, H. J. 1984 Comprehensive measurements in bubbly two-phase flows using laser-Doppler and hot-film velocimeter. *Chem. Engng Commun.* **28,** 29–43.

Castillejos, A. H. & Brimacombe, J. K. 1987 Measurement of physical characteristics of bubbles in gas–liquid plumes: Part II. Local properties of turbulent air–water plumes in vertically injected jets. *Metall. Trans.* **18B,** 659–671.

Durst, F. & Zare M. 1975 Laser Doppler measurements in two phase flows. *Proc. of the LDA Symp.*, Copenhagen, pp. 403–429.

Durst, F., Schonung, B., Selanger, K. & Winter, M. 1986 Bubble driven liquid flows. *J. Fluid Mech.* **170,** 53–82.

Iguchi, M., Nozawa, K., & Morita, Z. 1991 Bubble characteristics in the momentum region of air–water vertical bubbling jet. *ISIJ Int.* **31,** 952–959.

Iguchi, M., Nozawa, K., Tomida, H. & Morita, Z. 1992 Bubble characteristics in the buoyancy region of a vertical bubbling jet. *ISIJ Int.* **32,** 747–759.

Iguchi, M., Kawajiri, A., Tomida, H. & Morita, Z. 1993 Effects of the viscosity of liquid on the characteristics of vertical bubbling jet in a cylindrical vessel. *ISIJ Int.* **33,** 361–368.

LEE, S. L. & SCREENIVASAN, J. 1982 An LDA technique for *in situ* simultaneous velocity and size measurement of large spherical particle in two-phase suspension flow. *Int. J. Multiphase Flow* **8,** 47–57.

MARIE, J. L. & LANCE, M. 1983 Turbulence measurements in two-phase bubbly flows using laser Doppler anemometry. In *Measuring Techniques in Gas–Liquid Two Phase Flow*, pp. 141–148. Springer, New York.

OHBA, K., YUHARA, T. & MATSUYAMA, H. 1986 Simultaneous measurements of bubble and liquid velocities in two-phase bubbly flow using LDA. *Bull. JSME* **29**(254), 2487–2493.

SHENG, Y. Y. & IRONS, G. A. 1991 A combined laser Doppler anemometry and electrical probe diagnostic for bubbly two-phase flow. *Int. J. Multiphase Flow* **17,** 585–598.

TSUJI, Y. & MORIKAWA, Y. 1982 LDV measurement of an air-solid two-phase flow in a horizontal pipe. *J. Fluid Mech.* **120,** 385–409.

UEMURA, T., IGUCHI, M., KAWABATA, H., & MORITA, Z. 1990 Velocity measurement in a gas injection vessel using multi-particle tracking method. *Proc. 6th Int. Iron and Steel Congress*, Vol. 1, pp. 477–482.