

Chapter 2

Turbulence Structure of Two-Phase Jets

2.1 Mean Flow Characteristics

2.1.1 Introduction

Gas injection techniques have been extensively used for current steelmaking processes, such as converters, ladles, RH degassing processes, and other metals refining processes. In order to enhance the efficiency of these processes, precise information on the behavior of rising bubbles in a molten metal bath and resultant molten metal flow induced by the bubbles is required. Since it is difficult to study bubble and liquid flow characteristics using actual processes, many experimental and theoretical model investigations have been carried out. Details of the previous investigations should be referred to, for example, a review article by Mazumdar and Guthrie [1].

Concerning the bubble characteristics specified by gas holdup α , bubble frequency f_B , mean bubble rising velocity u_B , and mean bubble chord length L_B in a high temperature molten metal bath agitated by bottom gas injection, hot model experiments have been carried out for molten copper and molten iron baths using a newly developed two-needle electro-resistivity probe [2–5]. In the axial region far from the nozzle exit, experimental results of α , f_B , u_B , and L_B for iron–Ar systems at 1,250 and 1,600°C and a copper–Ar system at 1,250°C were found to be predicted satisfactorily by empirical correlations derived originally for a water–air and a mercury–air system [6, 7] as long as the radial distributions of gas holdup and bubble frequency follow Gaussian distributions.

Compared with the bubble characteristics, the information on the liquid flow characteristics specified by the axial and radial mean velocities, u and v , the root-mean-square values of the axial and radial turbulence components, u'_{rms} and v'_{rms} , the Reynolds shear stress $\overline{u'v'}$, and higher correlations of turbulence components, such as the skewness and flatness factors, are limited except for a water–air system [8–12].

In general, precise measurements of the liquid flow characteristics in a molten metal bath at high temperatures are very difficult. At present, the mean velocity can be measured under limited conditions by using reaction probes [13–16] and Karman

vortex probes [17, 18] even if the bath temperature is higher than 1,000°C, whereas the measurement of turbulence is practically impossible in this temperature range.

Numerical simulation techniques therefore have acted as a bridge between water models and actual processes [19, 20]. The aforementioned liquid flow characteristics in a molten metal bath agitated by gas injection were predicted numerically by using turbulence models, such as the $k - \varepsilon$ model, developed originally for single-phase flows [19, 20]. Numerical results thus obtained, however, have not received reliable experimental confirmation even for mercury and Wood's metal flows.

In this section, a description is provided of the bubble and liquid flow characteristics measured in a molten Wood's metal bath stirred by bottom helium gas injection. The aim is to provide experimental data for judging the adequacy of numerical results and to examine whether the results of liquid flow characteristics obtained for a water–air system are useful to predict molten metal flows.

A magnet probe, specifically the Vives probe, [21, 22] was used to measure the mean velocity and turbulence components of molten Wood's metal flow at around 100°C. Helium gas was chosen to simulate the density ratio between molten steel and Ar.

2.1.2 Experiment

2.1.2.1 Bubble characteristics

Figure 2.1 shows a schematic diagram of the experimental apparatus. The cylindrical vessel made of stainless steel had an inner diameter D of 20.4 cm and a height H of 30.0 cm. Wood's metal (commercial name: U-alloy 70, melting temperature: 70°C) was melted in it to a depth, H_L , of 15.0 cm. The bath temperature was kept at $105 \pm 1^\circ\text{C}$ using a thermo-controller. The physical properties of the molten Wood's metal are as follows: density $\rho_s = 9.56 \text{ g/cm}^3$, kinematic viscosity $\nu_s = 0.341 \text{ mm}^2/\text{s}$, and surface tension $\sigma = 460 \text{ mN/m}$.

Helium gas was preheated up to $105 \pm 5^\circ\text{C}$ with a heat exchanger installed upstream of the vessel and injected at a flow rate Q_g of $60 \text{ Ncm}^3/\text{s}$ through a centered single-hole bottom nozzle with an inner diameter, d_{ni} , of 0.5 mm. Therefore, it is not necessary to consider the expansion of gas at the nozzle exit due to temperature difference between the bath and the injected gas. The density ratio of the molten Wood's metal to the Helium gas is the same order of magnitude as that of steel to Ar. The nozzle was made of fluororesin (commercial name: Teflon). The origin of the axial and radial coordinates, z and r , were placed at the center of the nozzle exit. The volumetric gas flow rate at the nozzle exit was $67 \text{ cm}^3/\text{s}$. Some additional measurements were made for $Q_g = 95 \text{ Ncm}^3/\text{s}$.

Gas holdup α , bubble frequency f_B , mean bubble rising velocity u_B , and mean bubble chord length L_B were measured using a two-needle electroresistivity probe (not shown in Fig. 2.1). The vertical distance between the tips of the two electrode needles was set at 2 mm. The output signals of the electroresistivity probe system

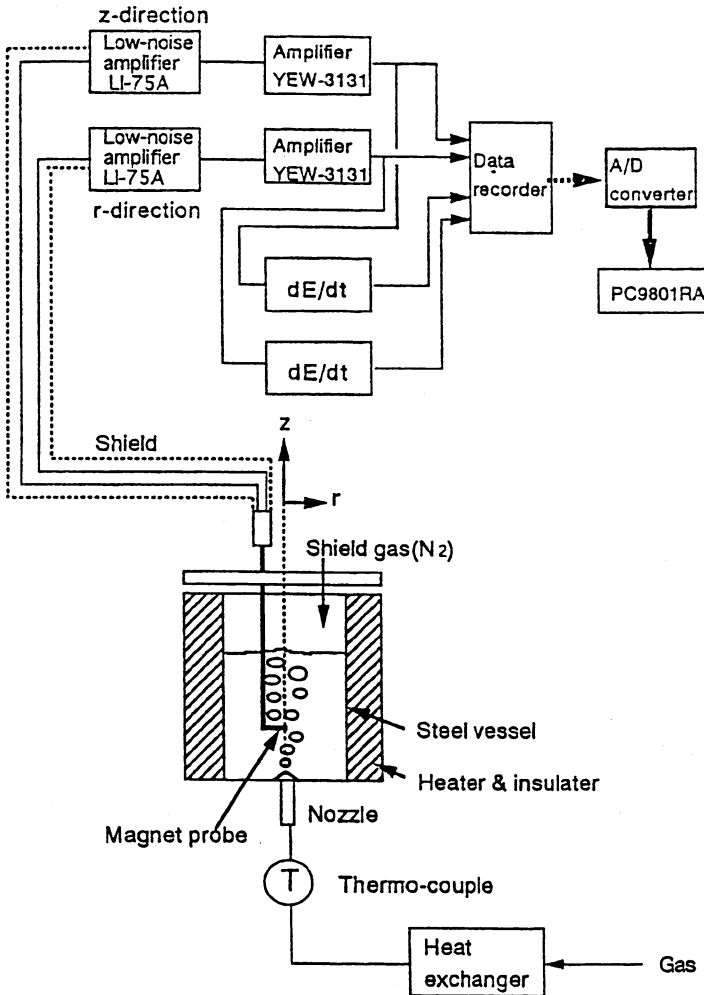


Fig. 2.1 Experimental apparatus

were A/D converted and then processed on a personal computer to determine these quantities. Further details of the measurement method should be referred to a previous paper [6, 7]. A special consideration was provided to prevent oscillations of the electrode needles induced by quasi-periodical arrival of bubbles. The measurement errors were approximately $\pm 3\%$ for α and f_B and $\pm 5\%$ for u_B and L_B .

Electroresistivity probe measurements were carried out on the centerline of the bubbling jet at equal intervals of 1 cm. Also, the radial distributions of the bubble characteristics were measured at four representative axial positions of $z = 1.5, 4.0, 7.0$, and 10.0 cm. The experimental results were compared with empirical relations proposed previously by Iguchi et al. [6, 7] for an arbitrary combination of metal and gas and with those proposed by Xie et al. [23] for a molten Wood's metal-N₂ system.

2.1.2.2 Liquid Flow Characteristics

The axial and radial velocity components, u and v , were measured by means of a two-channel magnet probe. The magnet probe works on the basis of Faraday's law [21, 22]. According to Weissenfluh, [22] if an electric conductor moves through a magnetic field, the conductor has an electromotive force induced in it which is in a direction normal to the magnetic field and the direction of motion. The electromotive force generates an electric field which is nearly proportional to the intensity of the magnetic field and to the velocity of the conductor. Therefore, it is possible to measure the velocity of the conductor by detecting the electromotive force. Further details of the working principle of the magnet probe are found in the articles of Ricou and Vives [21] and Weissenfluh [22].

The magnet probe is applicable to molten metal flows at a temperature lower than the Curie point of the permanent magnet. Previous magnet probe measurements for a Wood' metal bath were carried out by Xie et al. [23] at bath temperatures lower than 150°C . The magnet probe used by Xie et al. cannot detect the axial and radial velocity components simultaneously. Accordingly, data on the Reynolds shear stress and higher order turbulence correlations, such as the skewness and flatness factors, have not been published.

An outline of the magnet probe described here is illustrated in Fig. 2.2. The original output voltage of the magnet probe is basically small (approximately $50\text{ }\mu\text{V}$) under normal conditions, and hence, two amplifiers are necessary (see Fig. 2.1). The original voltage was amplified by 10,000 (100×100) times and then recorded on a data recorder. Signals originating from bubbles were removed using a differentiating

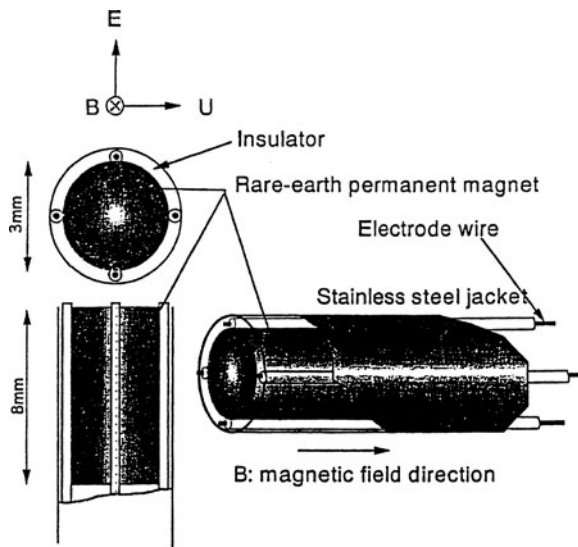


Fig. 2.2 Schematic of the present magnet probe

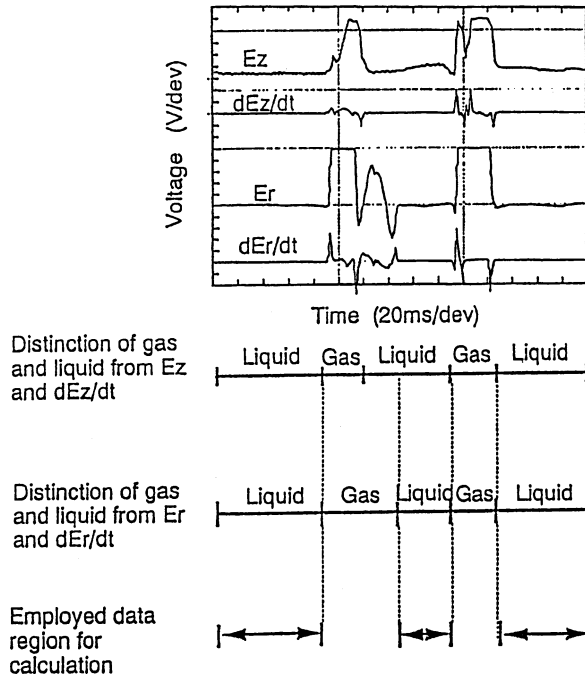


Fig. 2.3 Discrimination of gas and liquid signals

circuit and a personal computer in a manner shown in Fig. 2.3, where E_z and E_r denote the output voltage values for the axial and radial velocity components, respectively, and t is time.

The measurement of the radial velocity component, v , is relatively more difficult than the axial velocity component, u , because the magnitude of v is much smaller than that of u . The errors in measuring u are estimated to be $\pm 5\%$, while those for v are $\pm 10\%$. The time required for measuring the Reynolds shear stress is basically quite long. Thus, the measurement at only one axial position $z = 4$ cm was done.

2.1.3 Experimental Results

2.1.3.1 Bubble Characteristics

Axial distribution

Figures 2.4–2.7 show measured values of gas holdup, α_{cl} , bubble frequency, $f_{B,cl}$, mean bubble rising velocity, $u_{B,cl}$, and mean bubble chord length, $L_{B,cl}$, where the subscript cl designates the value on the centerline of the bath. In Fig. 2.4, the

Fig. 2.4 Axial distributions of gas holdup on the centerline

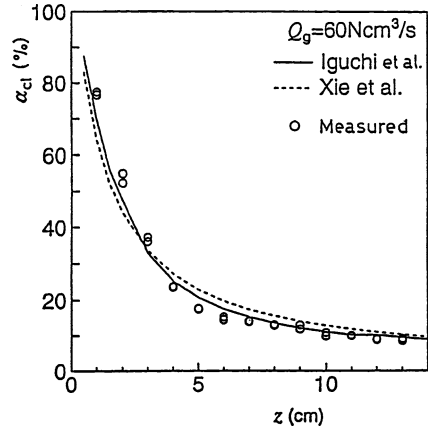
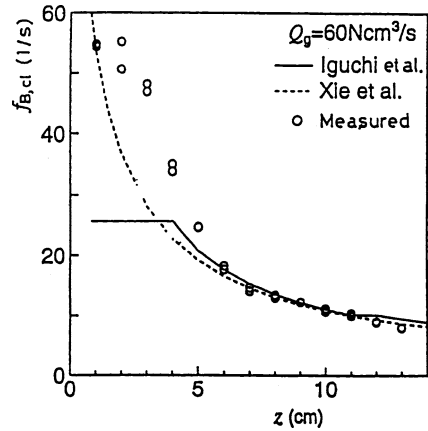


Fig. 2.5 Axial distributions of bubble frequency on the centerline



measured α_{cl} values are approximated satisfactorily by two empirical equations [6, 7, 23]. The same degree of agreement between the measured $f_{B,cl}$ values and two empirical equations can be seen for $z > 5$ cm, as shown in Fig. 2.5. The axial distribution of the mean bubble rising velocity on the centerline, $u_{B,cl}$, shown in Fig. 2.6, is well correlated by the empirical relation of Xie et al. [23] in the axial region of $z > 5$ cm. However, it is not reasonable to judge the adequacy of the empirical correlations by focusing solely on the centerline values, as can be seen from comparisons between the empirical correlations and measured radial distributions of the bubble characteristics shown in a subsequent section.

In Fig. 2.7, the measured $L_{B,cl}$ distribution for $z > 5$ cm is also approximated satisfactorily by the empirical correlation of Xie et al. [23]. The measured $L_{B,cl}$ value obtained at $z = 1$ cm is much larger than 2 cm, implying that the bubble generation region extends far beyond $z = 2$ cm. Consequently, the measured $u_{B,cl}$ value in the close vicinity of the nozzle exit does not present the real bubble

Fig. 2.6 Axial distributions of mean bubble rising velocity on the centerline

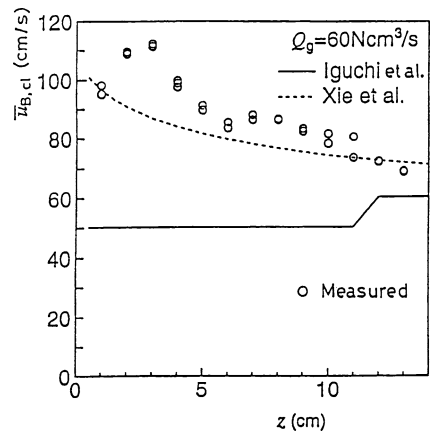
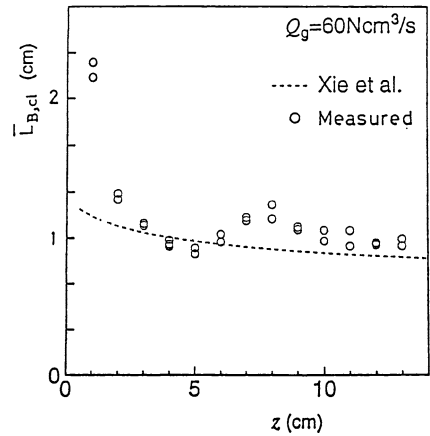


Fig. 2.7 Axial distributions of mean bubble chord length on the centerline



rising velocity of a bubble but includes the contribution of the expansion velocity of the bubble. A peak appearing at around $z = 2.5$ cm in the axial distribution of $u_{B,cl}$ shown in Fig. 2.6 may be considered to be related to such an expansion velocity.

Radial distribution

The radial distributions of gas holdup, α , measured by Iguchi et al. [24] at four representative axial positions are shown in Fig. 2.8. The α distribution at $z = 1.5$ cm is very steep near the centerline of the bubbling jet. Two peaks appeared in the α distributions measured at $z = 4.0$ and 7.0 cm. These two peaks are not caused by the swirl motion of a bubbling jet because no swirl motion was observed under the

Fig. 2.8 Radial distributions of gas holdup

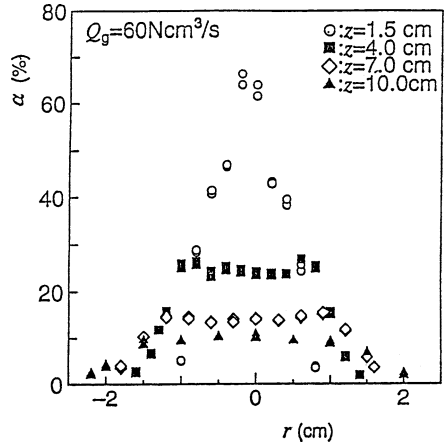
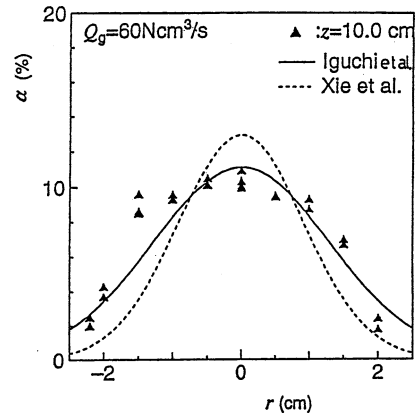


Fig. 2.9 Radial distributions of gas holdup at $z = 10$ cm



experimental conditions considered. They are closely associated with the shape of bubbles like a bell commonly seen in oriental temples [25].

Although any evidence is not given, agreement between the measured α values and the empirical correlations is not good at $z = 4.0$ and 7.0 cm because these two correlations assume Gaussian distributions. The measured radial distribution of α approached a Gaussian distribution as z increased further (see α distribution at $z = 10$ cm). As a result, the measured α values at $z = 10$ cm were approximated adequately by the empirical correlation by Iguchi et al. [6, 7], as demonstrated in Fig. 2.9.

In Fig. 2.10, showing the radial distributions of bubble frequency f_B , a plateau appeared in the distributions at $z = 4.0$ and 7.0 cm. This is also attributed to the formation of bell-shaped bubbles [25]. The radial f_B distribution measured at

Fig. 2.10 Radial distributions of bubble frequency

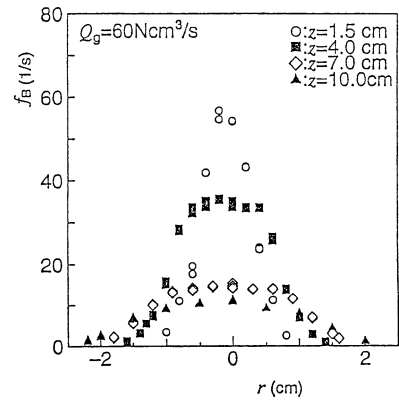
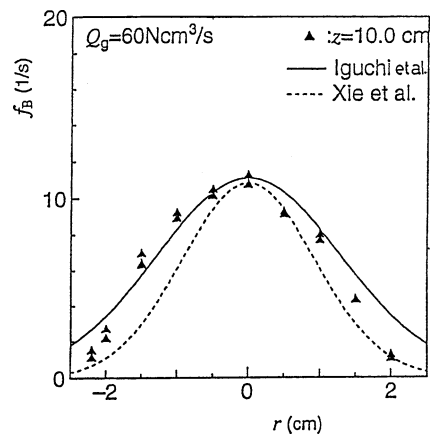


Fig. 2.11 Radial distributions of bubble frequency at $z = 10$ cm



$z = 10.0$ cm was also predicted by the two empirical correlations (see Fig. 2.11) to within approximately the same accuracy.

Figures 2.12 and 2.13 show the radial distributions of mean bubble rising velocity u_B and mean bubble chord length L_B , respectively. The measured values of u_B and L_B at $z = 1.5$ cm were not plotted. The relatively large u_B values near the centerline ($r \cong 0$) at $z = 4$ and 7 cm may be caused by the vertical elongation of bell-shaped bubbles [25]. The empirical correlation of u_B proposed by Iguchi et al. [6, 7] can predict the measured values only in the outer region of the bubbling jet. At every axial position, the measured L_B value is relatively small near the centerline, being caused by thinning of the bell-shaped bubbles. Any empirical correlations for the radial distributions of u_B and L_B were not proposed by Xie et al.

A reexamination of previous experimental results for an Fe-Ar system, [2, 3, 5] a Cu-Ar system [4], and a Wood's metal- N_2 system [26] reveals that the radial distributions of α , f_B , u_B , and L_B are similar to those mentioned above near the nozzle exit, although each radial distribution is not so distinguished compared with the results presented in Figs. 2.12 and 2.13.

Fig. 2.12 Radial distributions of mean bubble rising velocity

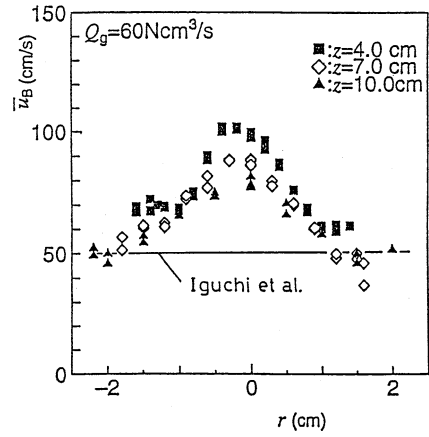
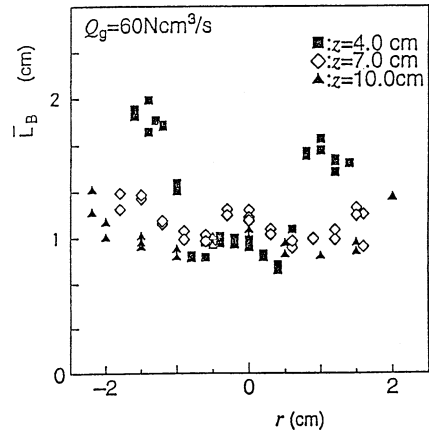


Fig. 2.13 Radial distributions of mean bubble chord length



Iguchi et al. [6, 7] did not observe two peaks in the radial distribution of α for a water–air system and a mercury–air system. For the water–air system, this might be because even if bell-shaped bubbles are generated, they are likely to disintegrate into smaller bubbles in complex shapes near the nozzle exit due to low surface tension and high turbulent shear stress of liquid flow.

Two peaks did not appear in α distributions for the mercury–air system, either. The surface tension of mercury is nearly equal to that of the Wood’s metal, but the density ratio ρ_L/ρ_g for the mercury–air system is much lower than that of the Wood’s metal–He system, where the subscripts L and g designate liquid and gas, respectively. Consequently, the density ratio ρ_L/ρ_g seems to be another candidate responsible for the difference in the bubble characteristics near the nozzle exit [27, 28].

2.1.3.2 Liquid Flow Characteristics

Axial Distribution

Figure 2.14 shows the axial mean velocity on the centerline of the bath, u_{cl} , and the root-mean-square values of the axial and radial turbulence components, $u'_{rms,cl}$ and $v'_{rms,cl}$, against the axial distance, z . The measured $\bar{u}_{cl}$ value remains almost unchanged in the axial direction and approaches the following empirical correlations originally proposed for a water–air system [9]:

$$\bar{u}_{cl} = 2.3u_r Fr_m^{0.036} (0.1 < P < 0.5) \quad (2.1)$$

$$= 1.2u_r P^{-0.28} (0.02 < P < 0.1) \quad (2.2)$$

$$Fr_m = \rho_g Q_g^2 / (g d_{ni}^5 \rho_L) \quad (2.3)$$

$$u_r = (g Q_g / z)^{1/3} \quad (2.4)$$

$$P = [Q_g^2 / (g z^5)]^{1/5} \quad (2.5)$$

where u_r is a representative velocity (cm/s), Fr_m is the modified Froude number, g is the acceleration due to gravity (cm/s^2), and P is a dimensionless parameter [9]. The units of u_{cl} , ρ_g , Q_g , ρ_L , d_{ni} , and z are cm/s, g/cm³, cm³/s, g/cm³, cm, and cm, respectively.

The axial turbulence intensity on the centerline, $u'_{rms,cl}/\bar{u}_{cl}$, is about 0.55 in the axial region except near the nozzle exit. The radial turbulence intensity on the centerline, $v'_{rms,cl}/\bar{u}_{cl}$, is also approximately 0.55 for the Wood's metal–He system. It is known that $u'_{rms,cl}/\bar{u}_{cl} = 0.5$ and $v'_{rms,cl}/\bar{u}_{cl} = 0.4$ for a water–air system. The measured values of $u'_{rms,cl}/\bar{u}_{cl}$ are almost the same for the two systems, whereas those of $v'_{rms,cl}/\bar{u}_{cl}$ are significantly different. This difference seems to be due mainly to the difference in the shapes of bubbles that influence the turbulence production in the wake of the bubbles.

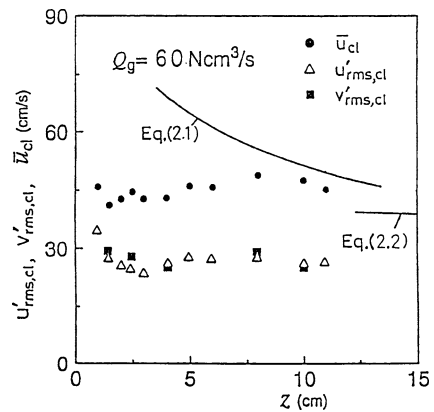


Fig. 2.14 Axial mean velocity and the rms values of turbulence components on the centerline as functions of axial distance

Fig. 2.15 Radial distributions of axial mean velocity

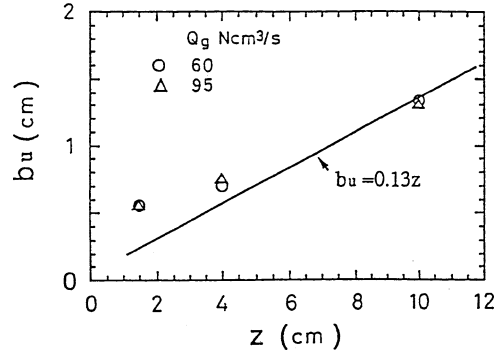
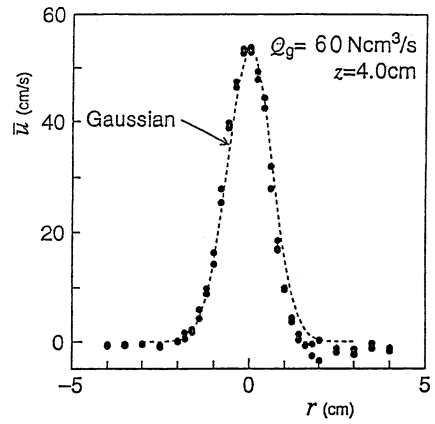


Fig. 2.16 Comparison of radial distributions of $\bar{u}$ between Wood's metal–He and water–air systems



The measured values of the half-value radius, b_u , of the radial distribution of $\bar{u}$ are shown in Fig. 2.15. The b_u value approaches the following empirical correlation as z increases:

$$b_u = 0.13z \quad (2.6)$$

This relation is known to hold for a water–air system [11].

Radial Distribution

The radial distribution of the axial mean velocity $\bar{u}$ measured at $z = 4$ cm is shown in Fig. 2.16. In the bubbling jet region ($r/b_u < 1.5$) where almost all rising bubbles are present, the radial $\bar{u}$ distribution is approximated satisfactorily by a Gaussian distribution marked by the broken line, although the radial α distribution does not follow a Gaussian distribution, as shown in Fig. 2.7. Measured $\bar{u}$ values for $z = 10$ cm are also approximated by a Gaussian distribution.

Fig. 2.17 Relation between half-value radius and axial distance

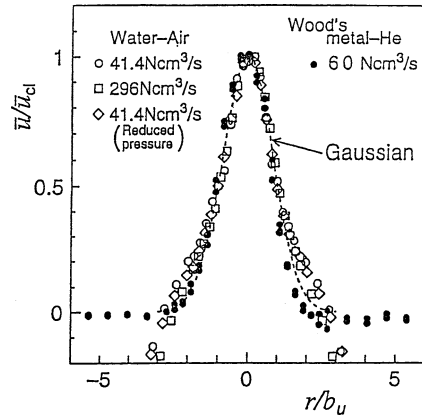
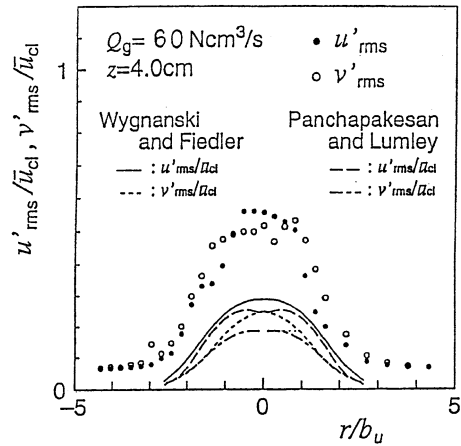


Fig. 2.18 Radial distributions of the rms values of axial and radial turbulence components



The measured $\bar{u}$ values shown in Fig. 2.16 and those obtained at an other measurement position ($z = 10$ cm) are nondimensionalized by $\bar{u}_{cl}$ and replotted against r/b_u in Fig. 2.17. The measured values of $\bar{u}/\bar{u}_{cl}$ for a water–air system are also included. The radial distributions of $\bar{u}/\bar{u}_{cl}$ for the two systems agree with each other for $r/b_u < 1.5$.

Figure 2.18 compares the radial distributions of the rms values of the axial and radial turbulence components, u'_{rms} and v'_{rms} , measured at $z = 4$ cm in the Wood's metal bath with those for single-phase free jets [29, 30]. Due to additional turbulence production in the wake of bubbles, the measured $u'_{rms}/\bar{u}_{cl}$ and $v'_{rms}/\bar{u}_{cl}$ values for the bubbling jet in the Wood's metal bath are much larger than those for the single-phase free jets [11]. The measured $u'_{rms}/\bar{u}_{cl}$ and $v'_{rms}/\bar{u}_{cl}$ values for the Wood's metal–He system are nearly the same both in the bubbling jet and recirculation regions. The latter region is located outside the former.

Fig. 2.19 Radial distributions of the rms values of axial turbulence component

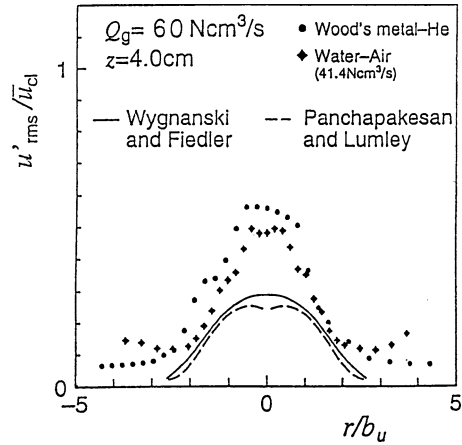
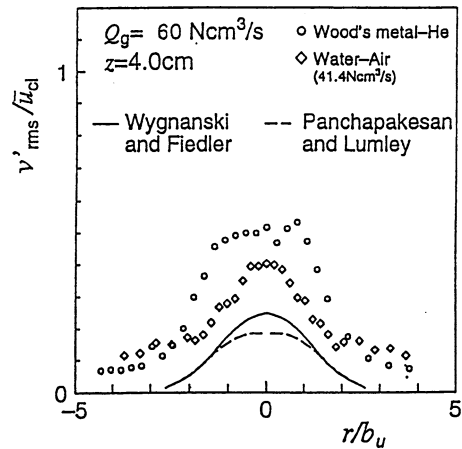


Fig. 2.20 Radial distributions of the rms values of radial turbulence component

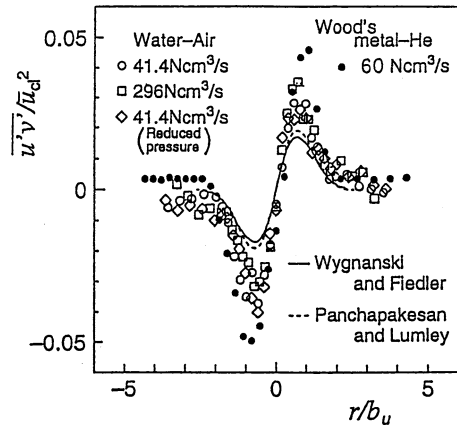


The measured rms values of the axial and radial turbulence components shown in Fig. 2.18 are replotted in Figs. 2.19 and 2.20, respectively. The values for a water-air system are also shown in these figures [10, 11]. In Fig. 2.19, agreement between the measured $u'_{rms}/\bar{u}_{cl}$ values for the Wood's metal-He system and the water-air system is quite good in the bubbling jet region ($r/b_u < 1.5$). Meanwhile, in Fig. 2.20, the Wood's metal-He system exhibits a relatively large $v'_{rms}/\bar{u}_{cl}$ value compared with the water-air system. Such a difference seems to be caused mainly by the difference in the turbulence production in the wake of the bubbles [25].

In the recirculation region, the measured values of $u'_{rms}/\bar{u}_{cl}$ and $v'_{rms}/\bar{u}_{cl}$ for the Wood's metal-He system are the same, as observed for a water-air system [8, 11, 12].

The radial distributions of the Reynolds shear stress $\overline{u'v'}$ are shown in Fig. 2.21. In the bubbling jet region, $r/b_u < 1.5$, the values for the Wood's metal-He system

Fig. 2.21 Radial distributions of the Reynolds shear stress



are much larger than those for a single-phase free jet because of the additional turbulence production in the wake of bubbles. Furthermore, the measured values of $\overline{u'v'}$ for the Wood's metal-He system are slightly larger than those for a water-air system. As mentioned above, this difference seems also to be attributable to the shape of bubbles.

2.2 Conditional Sampling

2.2.1 Introductory Remarks

Many experimental studies have been carried out to investigate the turbulence characteristics in gas-liquid and gas-solid two-phase jets under various flow conditions [31–35]. In single-phase jets, turbulence is produced mainly by entrainment of surrounding fluid into the jets, [29, 30] while in two-phase jets, turbulence production takes place also in the wake of bubbles or solid particles in addition to turbulence production due to the entrainment typical of single-phase jets. The size and shape of bubbles or solid particles are considered to affect the structure of turbulence [36, 37]. The effects of the size of bubbles or solid particles on the modulation of turbulence characteristics have been reported by many researchers [35–38]. However, the information on the effect of bubble shape is quite limited.

As shown in the previous section, the shape of bubbles was found to affect preferably the modulation of radial (horizontal) turbulence component [24]. However, the mechanism of turbulence production was not mentioned. In this section, the application is described of the four-quadrant classification method, [39] one of the most popular conditional sampling methods, adopted to elucidate the coherent structure of turbulence or the mechanism of turbulence production in a He-Wood's metal bubbling jet.

2.2.2 Experimental Apparatus and Procedure

A detailed description of the apparatus and experimental method for molten Wood's metal flow has been provided in the preceding section.

2.2.3 Shape and Size of Helium Bubble

Before discussing the turbulence structure in a bubbling jet in detail, it is worth describing first the shape and size of bubbles. The radial distribution of gas holdup in a vertical bubbling jet is widely known to obey a Gaussian distribution when bubbles can be classified as the so-called wobbling type, as schematically shown in Fig. 2.22 [40]. The axial mean velocity of liquid flow also follows a Gaussian distribution in the presence of wobbling bubbles [39]. Under the experimental condition being described here, the radial distribution of gas holdup has a plateau near the centerline of the bubbling jet and exhibits a mild peak outside the plateau. This somewhat curious distribution of gas holdup can be explained as follows.

The cross-section of bubbles was observed using a multi-needle electroresistivity probe [25]. The bubbles have a cross-section illustrated in Fig. 2.23, and could be classified into the well-known skirted type. This kind of bubble appears when the following modified Weber number, We_m , and the Reynolds number, Re_m , are relatively small [41].

$$We_m = (\rho_g/\rho_L)\rho_L d_B u_B^2/\sigma, \quad (2.7)$$

$$Re_m = (\rho_g/\rho_L)d_B u_B/\nu_L, \quad (2.8)$$

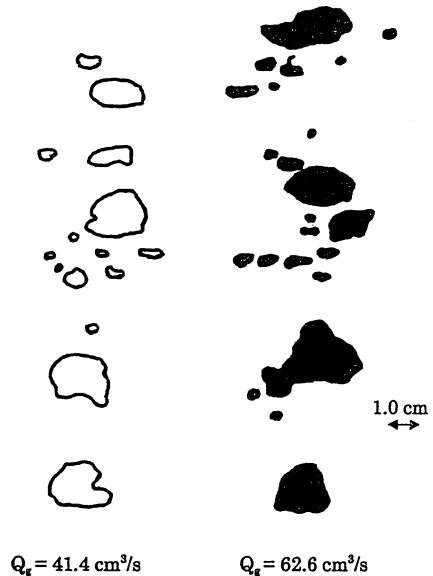
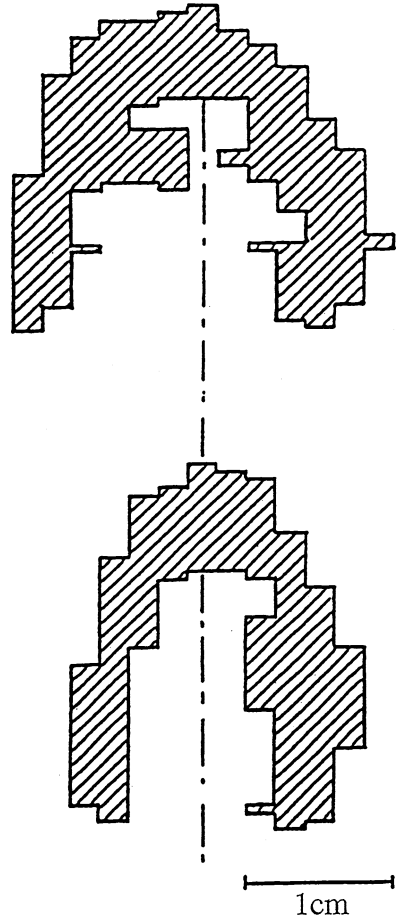


Fig. 2.22 Shape of bubbles visualized with a high-speed video camera in air–water system

Fig. 2.23 Measured bubble shape at $z = 0.050$ m in He–Wood’s metal bubbling jet

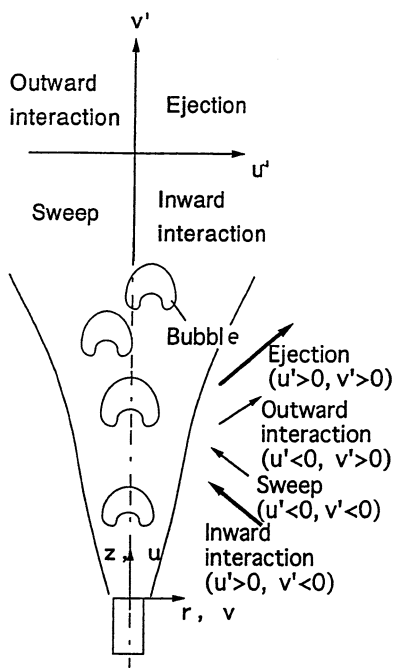


where ρ_g is the density of gas, ρ_L is the density of liquid, d_B is the mean bubble diameter, u_B is the mean bubble rising velocity, σ is the surface tension of liquid, and ν_L is the kinematic viscosity of liquid.

2.2.4 Four-Quadrant Classification Method

Turbulent motions in single-phase boundary layers, pipe flows, and jets are not completely random but have coherent or ordered structure [42–45]. According to the four-quadrant classification method, the turbulent motions are grouped into four distinct categories, as illustrated in Fig. 2.24. In this figure, “ejection” denotes a higher momentum fluid motion directed outward, “outward interaction” denotes a lower momentum fluid motion directed outward, “sweep” denotes a lower momentum

Fig. 2.24 Classification of turbulent motions



fluid motion directed inward and “inward interaction” denotes a higher momentum fluid motion directed inward. The frequency of occurrence of these four turbulent motions, and their contributions to the turbulence kinetic energies and to the Reynolds shear stress, are discussed subsequently by comparing them with those for the air–water bubbling jet [39,45].

2.2.5 Experimental Results Based on Four-Quadrant Classification Method

Figure 2.25 shows the occurrence frequencies of the four turbulent motions in the He–Wood’s metal bubbling jet together with those in an air–water bubbling jet [25]. In the region near the center line ($r = 0$), the occurrence frequency of each turbulent motion is approximately 0.25, and hence, there is no coherent structure there. In a radial region of $0 < r/b_u < 1.0$, the occurrence frequency of sweep is the highest, followed by the ejection. The occurrence frequency of inward interaction is the lowest. The order of the first two motions is the same as that for an air–water bubbling jet [39]. As r/b_u becomes greater than approximately 1.0, around which the peak of gas holdup appeared, the occurrence frequency of sweep decreases drastically, while that of inward interaction increases. Consequently, the coherent structure for $r/b_u > 1.0$ in the He–Wood’s metal bubbling jet differs significantly from that in the air–water bubbling jet.

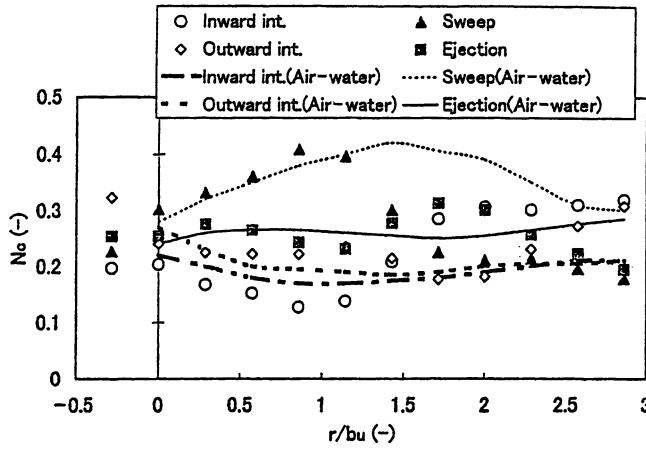
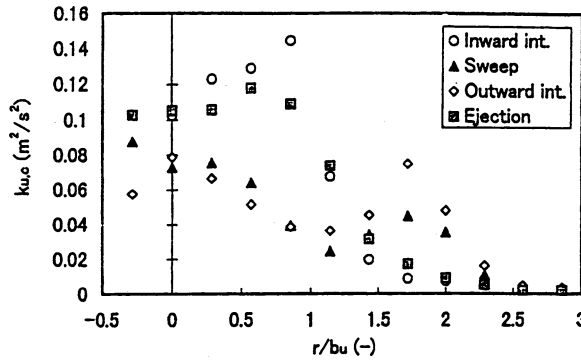
Fig. 2.25 Relative appearance frequency N_c 

Fig. 2.26 Radial distributions of the axial turbulence kinetic energy for each turbulent motion

Figure 2.26 presents the axial turbulence kinetic energy for each turbulent motion, $k_{u,c}$, calculated from the axial turbulence component u' , thus,

$$k_{u,c} = [\Sigma(u_i - u)^2]_c / N_c, \quad (2.9)$$

where the subscripts c and i designate each turbulent motion and the i th digitized datum, respectively. The contributions of ejection and inward interaction to the axial turbulence kinetic energy are dominant for $r/b_u < 1.0$. Although the appearance frequency of inward interaction is the lowest for $r/b_u < 1.0$, its contribution to the axial turbulence kinetic energy is the largest. For $r/b_u > 1.0$, the sweep and outward interaction play an important role on the axial turbulence kinetic energy.

Figure 2.27 compares the measured data on the contribution of each turbulent motion to the total turbulence kinetic energy in the axial direction with those in an

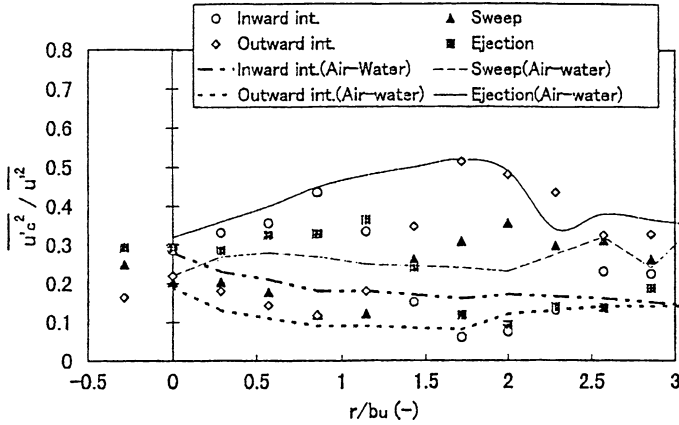


Fig. 2.27 Contributions of four turbulent motions to the axial turbulence kinetic energy

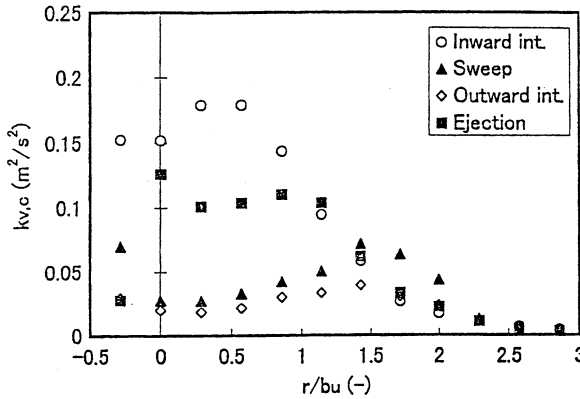


Fig. 2.28 Radial distributions of the radial turbulence kinetic energy for each turbulent motion

air–water bubbling jet [45]. The contribution of ejection is most dominant everywhere in the air–water bubbling jet, while in the Wood’s metal–He bubbling jet, the contribution of inward interaction is most dominant for $r/b_u < 1.0$ and that of outward interaction is so for $r/b_u > 1.0$. These results imply that the wake behind bubbles play an essential role on turbulent production in bubbling jets because the behavior of wake is closely associated with the shape and size of bubbles.

Figure 2.28 illustrates the radial turbulence kinetic energy for each turbulent motion. The contribution of inward interaction is particularly large for $r/b_u < 1.0$ in spite of its lowest appearance frequency just like the axial turbulence kinetic energy. Meanwhile, in this radial region ($r/b_u < 1.0$), the contributions of sweep and outward interaction are hardly different from each other.

Fig. 2.29 Radial distributions of Reynolds shear stress for each turbulent motion

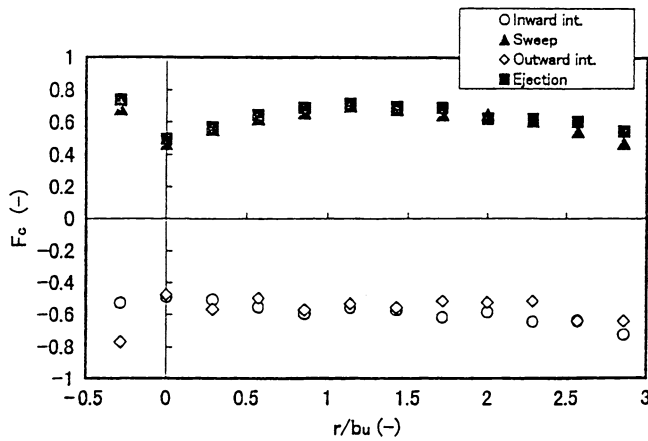
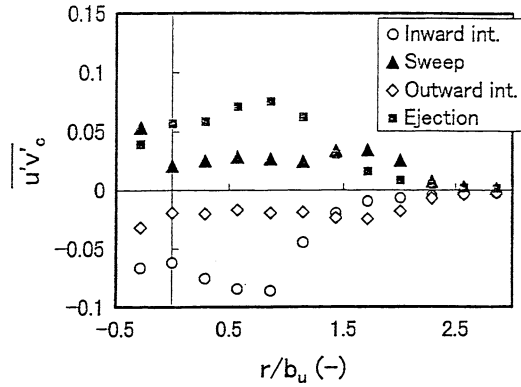


Fig. 2.30 Correlation factor for each turbulent motion

Figure 2.29 shows the radial distribution of the Reynolds shear stress for each turbulent motion. The absolute values for the inward interaction and ejection are large, as suggested from the turbulence kinetic energies.

Figure 2.30 shows the measured values of the correlation factor, F_c , defined by

$$F_c = \Sigma[(u_i - \bar{u})(v_i - \bar{v})]_c / [(\Sigma(u_i - \bar{u})^2)_c (\Sigma(v_i - \bar{v})^2)_c]^{1/2} \quad (2.10)$$

The measured values of F_c for each turbulent motion remain almost unchanged in the radial direction, but in a strict sense, those for ejection and sweep changed trend around $r/b_u = 1.0$. This implies that the He–Wood’s metal bubbling jet has two large-scale coherent structures, the boundary being located around $r/b_u = 1.0$. This result is consistent with the above-mentioned findings on the appearance frequency and the contributions of each turbulent motion to the turbulence kinetic energies and the Reynolds shear stress.

2.3 Summary

2.3.1 Mean Flow Characteristics

The bubble and liquid flow characteristics in a molten Wood's metal bath agitated by bottom Helium gas injection measured using a two-needle electroresistivity probe and a magnet probe, respectively, can be summarized as follows:

2.3.1.1 Bubble Characteristics

- (a) The axial distributions of gas holdup and bubble frequency on the centerline, α_{cl} and $f_{B,cl}$, for $z > 5$ cm are approximated satisfactorily by two empirical correlations [6, 7, 23]. The empirical correlations of Xie et al. [23] for the mean bubble rising velocity and the mean bubble chord length on the centerline, $u_{B,cl}$ and $L_{B,cl}$, also approximate adequately the measurement for $z > 5$ cm.
- (b) The radial distributions of gas holdup α and bubble frequency f_B measured at the axial position of $z = 1.5$ cm are very steep near the centerline of a bubbling jet. Two peaks appear in the α distributions at $z = 4.0$ and 7.0 cm. The two-peak distribution is closely associated with bell-shaped bubbles. Further downstream of the nozzle exit ($z = 10$ cm), the disintegration of bell-shaped bubbles occurs and the distributions of α and f_B are nearly Gaussian. The empirical distributions of α and f_B [6, 7, 23] can approximate the measured radial distributions only at $z = 10$ cm.

The mean bubble rising velocity u_B and mean bubble chord length L_B measured at $z = 1.5, 4.0$, and 7.0 cm, exhibit a complex behavior in the radial direction. These radial distributions are also closely related to the shape of bubbles. An empirical correlation of u_B is proposed that could approximate the measurements only at the outer region of a bubbling jet.

2.3.1.2 Liquid Flow Characteristics

- (a) In the axial region where the measured radial distribution of gas holdup α follows a Gaussian distribution, the axial mean velocity on the centerline, $\bar{u}_{cl}$, and the half-value radius of $\bar{u}$, denoted by b_u , are well correlated by empirical correlations derived originally for a water–air system. The axial turbulence intensity on the centerline, $u'_{rms,cl}/\bar{u}_{cl}$, is approximately 0.55 except near the nozzle exit. This value is nearly the same as that for the water–air system. The radial turbulence intensity on the centerline, $v'_{rms,cl}/\bar{u}_{cl}$, is also approximately 0.55 for the Wood's metal–He system, while it is about 0.4 for the water–air system. This difference seems to be due to the fact that the turbulence production in the wake of bubbles is dependent on the shape of the bubbles.

- (b) In the bubbling jet region ($r/b_u < 1.5$), the radial $\bar{u}$ distributions measured at axial positions except near the nozzle exit are Gaussian, as observed for a water–air system. The radial distributions of the axial turbulence intensity, $u'_{\text{rms}}/\bar{u}_{\text{cl}}$, measured at $z = 4$ and 10 cm also compare well with those for the water–air system. On the other hand, the radial distributions of the radial turbulence intensity, $v'_{\text{rms}}/\bar{u}_{\text{cl}}$, are larger for the Wood’s metal–He system than for the water–air system. As a result, the radial distributions of the Reynolds shear stress $\overline{u'v'}/\bar{u}_{\text{cl}}^2$ in the two systems are different from each other. This difference seems also to be attributable to the shape of bubbles.

In the recirculation region, the measured values of $u'_{\text{rms}}/\bar{u}_{\text{cl}}$ and $v'_{\text{rms}}/\bar{u}_{\text{cl}}$ are nearly equal as in the case of a water–air system.

The experimental results suggest that empirical correlations of the bubble characteristics and the axial mean velocity and turbulence components of liquid flow, derived from cold model experiments, are applicable to actual refining processes stirred by bottom gas injection when the radial distributions of gas holdup and bubble frequency follow Gaussian distributions. These distributions appear to be a result of the disintegration of rising bubbles due to highly turbulent liquid motion in the bath.

2.3.2 Conditional Sampling

A description is provided of the use of the 4-quadrant classification method, for measuring the coherent structure of turbulence in a He–Wood’s metal bubbling jet. The results were compared with those obtained in an air–water bubbling jet. The main findings can be summarized as follows.

There exist two different types of coherent structures with respect to the radial distance in a He–Wood’s metal bubbling jet. The boundary between the two types is located around $r/b_u = 1.0$. This radial position nearly corresponds to the outer edge of the bubble dispersion region. Most He bubbles rise in the radial region of $r/b_u < 1.0$. Turbulence is produced mainly by inward interaction for $r/b_u < 1.0$, and by outward interaction for $r/b_u > 1.0$.

There exists only one coherent structure of turbulence in an air–water bubbling jet. Turbulence is produced mainly by ejection everywhere in the bubbling jet. The difference in the turbulence structures in the two types of bubbling jets is attributable to the shape and size of bubbles. Bubbles in the He–Wood’s metal bubbling jet are of the skirted type, while those in an air–water bubbling jet adopted for comparison can be classified into the wobbling type.

References

1. Mazumdar D, Guthrie RIL (1995) The Physical and mathematical modelling of gas stirred ladle systems. *ISIJ Int* 35:1–20
2. Iguchi M, Kawabata H, Itoh Y, Nakajima K, Morita Z (1994) Continuous measurements of bubble characteristics in a molten iron bath with Ar gas bubbling. *Tetsu-to-Hagane* 80: 365–370
3. Iguchi M, Kawabata H, Nakajima K, Morita Z (1995) Measurement of bubble characteristics in a molten iron bath at 1600°C using an electroresistivity probe. *Metall Mater Trans B* 26B: 67–74
4. Iguchi M, Kawabata H, Nakajima K, Morita Z (1996) Bubble characteristics in molten copper bath with gas injection. *Trans Jpn Soc Mech Eng* 62–593:79–84
5. Iguchi M, Kawabata H, Itoh Y, Nakajima K, Morita Z (1996) Continuous measurements of bubble characteristics in a molten iron bath with Ar gas injection. *ISIJ Int* 34:980–985
6. Iguchi M, Demoto Y, Sugawara N, Morita Z (1992) Behavior of Hg-air vertical bubbling jet in a cylindrical vessel. *Tetsu-to-Hagane* 78:407–414
7. Iguchi M, Demoto Y, Sugawara N, Morita Z (1992) Bubble behavior in Hg-air vertical bubbling jets in a cylindrical vessel. *ISIJ Int* 32:998–1005
8. Iguchi M, Takeuchi H, Morita Z (1990) The flow field in air-water vertical bubbling jets in a cylindrical vessel. *Tetsu-to-Hagane* 76:699–706
9. Iguchi M, Kondoh T, Morita Z, Nakajima K, Hanazaki K, Uemura T, Yamamoto F (1995) Velocity and turbulence measurements in a cylindrical bath subject to centric bottom gas injection. *Metall Mater Trans B* 26:241–247
10. Sheng YY, Irons GA (1992) Measurements of the internal structure of gas-liquid plumes. *Metall Mater Trans B* 23:779–788
11. Iguchi M, Ueda H, Uemura T (1995) Bubble and liquid flow characteristics in a vertical bubbling jet. *Int J Multiphase Flow* 21:861–873
12. Iguchi M, Takeuchi H, Morita Z (1991) The flow field in air-water vertical bubbling jets in a cylindrical vessel. *ISIJ Int* 31:246–253
13. Hsiao TC, Lehner T, Kjellberg B (1978) Fluid flow in ladles – experimental results. *Scand J Metal* 9:105–110
14. Iguchi M, Kawabata H, Demoto Y, Morita Z (1991) Cold model experiment for developing a new velocimeter applicable to molten metal. *Tetsu-to-Hagane* 79:1046–1052
15. Mikrovass AC, Argyropoulos SA (1993) Measurement of velocity in high-temperature liquid metals. *Metall Mater Trans B* 24:1009–1022
16. Iguchi M, Kawabata H, Demoto Y, Morita Z (1994) Cold model experiments for developing a new velocimeter applicable to molten metal. *ISIJ Int* 34:461–467
17. Iguchi M, Takeuchi M, Kawabata H, Ebina K, Morita Z (1994) Development of a Kármán vortex probe for measuring the velocity of molten metal flow. *Trans JIM* 35:716–722
18. Iguchi M, Kawabata H, Ogura T, Hayashi A, Terauchi Y (1996) A new probe for directly measuring flow velocity in the continuous casting mold, Proc first int steelmaking conference, Chiba, Japan, *ISIJ*, p 40
19. Sawada I, Tani M, Szekely J, Ilegbusi OJ (1991) Recent developments and possibilities of computational fluid dynamics in materials processing. *Tetsu-to-Hagane* 77:1234–1242
20. Sahai Y, St. Pierre GR (1992) *Advances in transport processes in metallurgical systems*. Elsevier, Amsterdam
21. Ricou R, Vives C (1982) Local velocity and mass transfer measurements in molten metals using an incorporated magnet probe. *Int J Heat Mass Transf* 25–10:1579–1588
22. von Weissenfluh T (1985) Probes for local velocity and temperature measurements in liquid metal flow. *Int J Heat Mass Transf* 28–8:1563–1574
23. Xie Y, Orsten S, Oeters F (1992) Behaviour of bubbles at gas blowing into liquid wood's metal. *ISIJ Int* 32:66–75
24. Iguchi M, Tokunaga H, Tatemichi H (1997) Bubble and liquid flow characteristics in a wood's metal bath stirred by bottom helium gas injection. *Metall Mater Trans B* 28B:1053–1061

25. Iguchi M, Nakatani T, Kawabata H (1997) The shape of bubbles rising near the nozzle exit in molten metal baths. *Metall Mater Trans B* 28B:417–423
26. Kondoh H (1993) Bachelor's dissertation. Fac Eng Osaka Univ
27. Iguchi M, Takanashi N, Ogawa Y, Tokumitsu N, Morita Z (1994) X-ray fluoroscopic observations of bubble characteristics in a molten iron bath. *Tetsu-to-Hagane* 80–7:515–520
28. Iguchi M, Chihara T, Takanashi N, Ogawa Y, Tokumitsu N, Morita Z (1995) X-ray fluoroscopic observation of bubble characteristics in a molten iron bath. *ISIJ Int* 35–11:1354–1361
29. Wygnanski I, Fiedler H (1969) Some measurements in the self-preserving jet. *J Fluid Mech* 38–3:577–612
30. Panchapakesan NR, Lumley JL (1993) Turbulence measurements in axisymmetric jets of air and helium. Part 1. Air jet. *J Fluid Mech* 246:197–223
31. Theofanous TG, Sullivan J (1982) Turbulence in two-phase dispersed flows. *J Fluid Mech* 116:343–362
32. Mostafa AA (1992) Turbulent diffusion of heavy-particles in turbulent jets. *Trans ASME J Fluids Eng* 114:667–671
33. Tsuji Y, Morikawa Y (1982) LDV measurements of an air–solid two-phase flow in a horizontal pipe. *J Fluid Mech* 120:385–409
34. Lance M, Bataille J (1991) Turbulence in the liquid phase of a uniform bubbly air–water flow. *J Fluid Mech* 222:95–118
35. Longmire EK, Eaton JK (1992) Structure of a particle-laden round jet. *J Fluid Mech* 236: 217–257
36. Gore RA, Crowe CT (1989) Effect of particle size on modulating turbulent intensity. *Int J Multiphase Flow* 2:279–285
37. Hetsroni G (1989) Particles-turbulence interaction. *Int J Multiphase Flow* 5:735–746
38. Iguchi M, Okita K, Nakatani T, Kasai N (1997) Structure of turbulent round bubbling jet generated by premixed gas and liquid injection. *Int J Multiphase Flow* 23:249–262
39. Iguchi M, Nakatani T, Ueda H (1997) Model study of turbulence structure in a bottom blown bath with top slag using conditional sampling. *Metall Mater Trans B* 28B:87–94
40. Iguchi M, Nozaawa K, Tomida H, Morita Z (1992) Bubble characteristics in the buoyancy region of a vertical bubbling jet. *ISIJ Int* 32:747–753
41. Iguchi M, Nakatani T, Tokunaga H (1997) The shape of bubbles rising near the nozzle exit in molten metal baths. *Metall Mater Trans B* 28B:417–423
42. Brodkey RS, Wallace JM, Eckelmann H (1974) Some properties of truncated turbulence signals in bounded shear flows. *J Fluid Mech* 63:209–224
43. Kim J, Moin P, Moser P (1983) Turbulence statistics in fully developed channel flow at low Reynolds number. *J Fluid Mech* 177:133–166
44. Iguchi M (1988) The structure of turbulence in pulsatile pipe flow accompanied by relaminarization. *JSME Int J* 31:623–631
45. Iguchi M, Nakatani T, Okita K, Yamamoto F, Morita Z (1996) Turbulence in reactors agitated by bottom gas injection. *ISIJ Int Suppl* 36:38–41

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