Continuous Measurements of Bubble Characteristics in a Molten Iron Bath with Ar Gas Injection

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Present authors developed a new electro-resistivity probe being able to continuously measure bubble characteristics in a molten iron bath agitated by gas injection. The life of the probe was about two hours at a bath temperature of 1 250°C. The axial and radial distributions of gas holdup α , bubble frequency f_B , mean bubble rising velocity $\bar{u}_B$ and mean bubble diameter $\bar{d}_B$ were determined for the Ar gas flow rates of 50 and 100 cm³/s (at 1 250°C). The Ar gas was preheated up to 1 250°C and then injected through a single-hole centric bottom nozzle.

The results were compared with empirical correlations derived from cold and hot model experiments. The measured values of α , f_B and $\bar{u}_B$ in the upper part of the bath were approximated satisfactorily by correlations proposed by the present authors, but they did not agree with the experimental results of Kawakami *et al.* The measured values of $\bar{d}_B$ were a little smaller than predicted values by Sano *et al.* and Irons *et al.*

KEY WORDS: electro-resistivity probe; molten iron; bubbling jet; steelmaking; injection; gas holdup; bubble frequency; bubble rising velocity; bubble diameter.

1. Introduction

Recent extensive utilization of gas injection techniques promoted the fundamental research on bubble and liquid flow characteristics in molten metal baths. In the initial stage the so-called cold model experiments using water, mercury and molten Wood's metal baths were actively carried out to clarify the bubble and liquid flow characteristics and the mixing time^{1–5)} because these liquid materials are easy to handle. Empirical correlations of the bubble characteristics (gas holdup α , bubble frequency f_B , mean bubble rising velocity $\bar{u}_B$ and mean bubble diameter $\bar{d}_B$) of bubbling jet formed in a bath by gas injection have been proposed by many researchers including the present authors. However, the applicability of these correlations to the bubble characteristics in high temperature molten metal baths has hardly been studied.

In the second stage some experiments were performed on the bubble formation in high temperature molten metal baths.^{6–9)} Sano *et al.*^{6,7)} measured the bubble frequency generated at a single-hole nozzle exit in a molten silver bath at 1 000°C and in a molten iron bath at 1 600°C using a pressure sensor technique. Irons and Guthrie⁸⁾ employed a similar acoustic device and observed the Ar bubble formation at some kinds of nozzles immersed in a molten iron bath at 1 250°C. However, these researchers did not mention the characteristics of rising bubbles in the bath.

Recently, Kawakami *et al.*⁹⁾ measured the gas holdup, bubble frequency, mean bubble rising velocity, and mean bubble diameter in a molten iron and a molten copper bath at 1 250°C with a two-needle electro-resistivity probe. They used a carbon wire as the electrode needle of the probe. The life of the electrode needle was less than 3 min due to the serious erosion of the electrode needle. It was therefore difficult to measure the bubble characteristics continuously and systematically by using that probe.

The present authors have developed a new electro-resistivity probe being able to continuously measure the bubble characteristics in high temperature molten metal baths. The life of this probe was about 2 h in a molten iron bath at 1 250°C. Using this probe, the axial and radial distributions of gas holdup α , bubble frequency f_B , mean bubble rising velocity $\bar{u}_B$ and mean bubble diameter $\bar{d}_B$ in a molten iron bath at 1 250°C were systematically measured. The bath was agitated by Ar gas injection through a centric bottom nozzle. The experimental results were compared with empirical correlations derived from cold model experiments.

2. Some Aspects of a New Two-needle Electro-resistivity Probe

Materials with high resistivity against erosion and chemical reactions in a molten iron bath at high

Fig. 1. Resistivity for various refractory materials at high temperature.

Fig. 2. Electro-resistivity probe for measuring bubbles in molten iron bath.

temperatures must be chosen as the electrode needle. Mechanical strength also is one of important properties required for the insulator.

The resistivity of some candidate materials at high temperatures¹⁰⁻¹²⁾ are plotted in Fig. 1. A schematic view of a new two-needle electro-resistivity probe is shown in Fig. 2. The electrode needle of the electro-resistivity probe was made of a LaCrO₃ wire or a ZrO₂ wire because the erosion resistivity of these materials was very high and the electric resistance was relatively low as shown in Fig. 1. Al₂O₃ was used as the insulator. The vertical separation L_p between the lower and upper electrode needles was set at 2.5 mm. We were able to accurately measure the bubble characteristics in a molten iron bath at 1 250°C over 2 h using this electro-resistivity probe.

3. Experimental Apparatus and Procedure

Figure 3 shows a schematic view of the experimental apparatus. The carbon crucible having an inner diameter D of 90 mm and a height of 180 mm was placed in a Tamman furnace, and pig iron was melted in it. The bath depth was set at 120 mm and the bath temperature measured with a thermocouple was kept at 1 250°C. The components of molten iron are Fe: 95.1 wt%, C: 4.48 wt%, Si: 0.10 wt%, Mn: 0.20 wt%, P: 0.11 wt% and S: 0.001 wt%. Ar gas was injected into the bath through a centric single-hole bottom nozzle made of alumina at gas flow rates of 50 cm³/s and of 100 cm³/s. The inner and outer diameters of the nozzle were 1 mm and 6 mm, respectively (see Fig. 4). The gas flow rate was evaluated

Fig. 3. Experimental apparatus for measuring bubbles in molten iron bath.

Fig. 4. Shape of bottom blowing nozzle and measurement position of Ar gas temperature.

at 1 250°C and 101 kPa. The Ar gas flow rate was adjusted by using a mass flow meter. The origin of the coordinate system was placed at the center of the nozzle exit. The axial and radial coordinates were represented by z and r , respectively.

The temperatures of Ar gas measured using a thermocouple at 75 mm upstream from the nozzle exit were 910 and 870°C for the gas flow rates of 50 and 100 cm³/s, respectively. According to heat transfer calculation, the gas temperature was estimated to be approximately 1 250°C at 10 mm upstream from the nozzle exit. Accordingly it was not necessary to consider the gas expansion due to a temperature difference.

The electro-resistivity probe was attached to traverse equipment, preheated above the bath surface for more than 20 min and then gradually immersed into the molten iron bath in order to avoid heat shock.

The output signals of the two-needle electro-resistivity probe system were A/D converted at a sampling frequency of 2 kHz and subsequently processed on a personal computer. The wave forms of the signals were monitored with an oscilloscope during the measurements. A typical example of the wave forms is shown in Fig. 5. By adjusting the resistance of the electric circuit of the electro-resistivity probe system, the output voltage was set at 2 V when the electrode was surrounded by molten iron and at 0.5 V when the electrode was surrounded by

Fig. 5. Sketch of the output voltage of the probe using LaCrO_3 electrode at 1250°C .

Ar gas. The output voltage for liquid phase fluctuated with an amplitude of 0.05 V and a period of about 30 min due to the fluctuation of the voltage of the electric furnace. Whenever the deviation of the output voltage exceeded 0.1 V, the resistance of the system was adjusted so that the output voltage become 2 V again. The measurements were stopped when the adjustment of resistance became impossible.

Measurements on the bath centerline were continued until the number of reliable bubble rising velocity data exceeded 30. The measurement was repeated 5–10 times at each measurement position and the average value was determined. On the other hand, the measurement time at each radial position was set at 4 sec.

In the case of measuring the mean bubble rising velocity $\bar{u}_B$ and mean bubble diameter $\bar{d}_B$, when the bubble residence time at the tip of the upper electrode 2 was between 0.7 and 1.3 times as large as that at the tip of the lower electrode 1, these signals were treated as output signals from the same bubble. The bubble rising velocity $\bar{u}_B$ was obtained from $L_p/\Delta t$, where L_p is the vertical separation of the two electrode needles and Δt is delay time between the two electrode tips. Gas holdup α was defined as the ratio of the summation of bubble residence time at the tip of the electrode 1 to total measurement time. Bubble frequency f_B was the number of bubbles passing through the tip of the electrode 1 in one second. The mean bubble diameter $\bar{d}_B$ was defined by $\bar{d}_B = 1.5 \bar{L}_B$, where $\bar{L}_B$ was the mean chord length of a bubble and the bubble was assumed to have a spherical shape.⁹⁾

4. Experimental Results and Discussion

4.1. Axial Distributions of Bubble Characteristics

Figure 6 shows the gas holdup on the centerline of the bath, α_{cl} , for the Ar gas flow rates of $Q_g = 50 \text{ cm}^3/\text{s}$ and $Q_g = 100 \text{ cm}^3/\text{s}$, where z is the vertical distance from the nozzle exit. It should be noted that at each measurement position in Fig. 6 the measured values for $Q_g = 50 \text{ cm}^3/\text{s}$ (○) and $Q_g = 100 \text{ cm}^3/\text{s}$ (●) are slightly shifted to the left and right, respectively, in order to avoid overlapping. The scatter of data around the mean value is represented by an error bar.

The measured values of α_{cl} decreased monotonously from approximately 60 % near the nozzle exit ($z = 15 \text{ mm}$) to about 20 % near the bath surface ($z = 75 \text{ mm}$). The

Fig. 6. Axial distributions of gas holdup α_{cl} on the bath centerline in the molten iron bath with bottom blowing (1250°C). (Plots (○), (●) were slightly shifted to the left and right to avoid overlapping.)

Fig. 7. Axial distributions of bubble frequency $f_{B,cl}$ on the bath centerline in the molten iron bath with bottom blowing (1250°C). (Plots (○), (●) were slightly shifted to the left and right to avoid overlapping.)

solid line for $Q_g = 50 \text{ cm}^3/\text{s}$, which is valid for $z \geq 19.6 \text{ mm}$, and the broken line for $Q_g = 100 \text{ cm}^3/\text{s}$, which is valid for $z \geq 25.0 \text{ mm}$, in the Figure were calculated from an empirical correlation derived by the present authors⁴⁾ for the ratio of liquid density to gas density ρ_L/ρ_g from 800 to 12 000 and for $\alpha_{cl} = 10\text{--}50\%$. Under the present experimental conditions the density ratio ρ_L/ρ_g was approximately 21 000. Nevertheless, agreement between the present measured values in the molten iron bath and the empirical correlation for cold model was relatively good for each Ar gas flow rate.

Figure 7 plots the bubble frequency on the centerline of the bath $f_{B,cl}$. As the gas flow rate increased from 50 to $100 \text{ cm}^3/\text{s}$, $f_{B,cl}$ also increased at every axial position. The measured values for each gas flow rate were larger than the predicted values in the region near the nozzle exit and agreed very well with them in the region near the bath surface.

Figure 8 shows the mean bubble rising velocity on the bath centerline $\bar{u}_{B,cl}$. At $z = 15 \text{ mm}$, the measured values of $\bar{u}_{B,cl}$ for the two gas flow rates agreed well with each

Fig. 8. Axial distributions of mean bubble rising velocity $\bar{u}_{B,cl}$ on the bath centerline in the molten iron bath with bottom blowing (1250°C). (Plots (○, ●) were slightly shifted to the left and right to avoid overlapping.)

Fig. 9. Axial distributions of mean bubble diameter $\bar{d}_{B,cl}$ on the bath centerline in the molten iron bath with bottom blowing (1250°C). (Plots (○, ●) were slightly shifted to the left and right to avoid overlapping.)

other. As z increased, $\bar{u}_{B,cl}$ increased and approached 0.54 m/s for $Q_g = 50 \text{ cm}^3/\text{s}$ and 0.64 m/s for $Q_g = 100 \text{ cm}^3/\text{s}$ in the axial region of $z \geq 55 \text{ mm}$. Agreement between the measured values and the empirical correlation was relatively good in the region near the bath surface.

Figure 9 shows the axial distributions of mean bubble diameter on the bath centerline $\bar{d}_{B,cl}$. The measured values of $\bar{d}_{B,cl}$ exhibited almost the same value of 12 mm in the region near the nozzle exit for the two gas flow rates, gradually increased as z increased and became approximately 15 mm in the axial region of $z \geq 35 \text{ mm}$. Since the diameter of rising bubbles is approximately 15 mm, the axial position of $z = 15 \text{ mm}$ is located in the upper end of the bubble formation region. Therefore the mean bubble rising velocity measured at $z = 15 \text{ mm}$ does not represent the real rising velocity but the expanding velocity of a bubble on the nozzle exit. Also, the mean bubble diameter obtained at $z = 15 \text{ mm}$ does not represent the real mean bubble diameter.

It is widely accepted that the wettability between the nozzle material and molten metal plays an important

Fig. 10. Radial profiles of gas holdup α at different axial positions in the molten iron bath with bottom blowing (1250°C).

role for the bubble formation. Sano *et al.*⁷⁾ measured the mean bubble diameter $\bar{d}_B$ at the nozzle exit in the molten silver bath at 1000°C and the molten iron bath at 1600°C and proposed the following empirical correlation for the case of bad wettability by referring to empirical correlation derived by Davidson and Amick¹⁾ for a water-air system.

$$\bar{d}_B = [\{6\sigma d_{no}/(\rho_L g)\}^2 + \{0.54(Q_g d_{no}^{0.5})^{0.289}\}^6]^{1/6} \quad \dots(1)$$

where σ is the surface tension, d_{no} the outer diameter of the nozzle, g the acceleration due to gravity.

Equation (1) yielded $\bar{d}_B = 15.5 \text{ mm}$ for $Q_g = 50 \text{ cm}^3/\text{s}$ and $\bar{d}_B = 19 \text{ mm}$ for $Q_g = 100 \text{ cm}^3/\text{s}$, as shown in Fig. 9. In the case of $Q_g = 50 \text{ cm}^3/\text{s}$, Eq. (1) was able to satisfactorily predict the present measured values, but in the case of $Q_g = 100 \text{ cm}^3/\text{s}$, Eq. (1) overestimated present mean bubble diameter. Such discrepancy might be attributable to the difference in the measuring method. In this study the mean bubble diameter $\bar{d}_B$ was determined by multiplying the mean chord length by 1.5. Contribution of small bubbles, which were generated owing to disintegration of large bubbles coming from the nozzle exit, to the mean chord length was considered in this analysis. Meanwhile, Sane *et al.* evaluated the mean bubble diameter $\bar{d}_B$ at the nozzle exit using an acoustic method, and consequently, the contribution of small bubbles to $\bar{d}_B$ was not mentioned.

Irons *et al.*⁸⁾ also measured $\bar{d}_B$ in a molten iron bath at 1250°C using the same measuring method as Sano *et al.* Measured values of $\bar{d}_B$ for a nozzle with an outer diameter of 6.35 mm, being almost the same as the outer diameter of 6.0 mm employed in this study, fell between about 15 and 22 mm. These measured values were apparently larger than the present measured values. This discrepancy also might be caused by the difference in the measuring method.

4.2. Radial Distributions of Bubble Characteristics

Figure 10 shows the radial distributions of gas hold

Fig. 11. Radial profiles of bubble frequency f_B at different axial positions in the molten iron bath with bottom blowing (1250°C).

up α at four representative axial positions ($z = 15, 35, 55, 75$ mm) for the Ar gas flow rate $Q_g = 100 \text{ cm}^3/\text{s}$, where r is the horizontal distance from the nozzle centerline. The measured values of α ($\circ$) obtained in the radial positions close to the centerline of the bath was nearly 60% at $z = 15$ mm, and the half-value radius of α was about 7 mm. As z increased and approached the bath surface, the measured values of α abruptly decreased near the centerline of the bath. On the other hand, the half-value radius of α became large and, for example, was about 14 mm at $z = 75$ mm. Although the present gas flow rate of $Q_g = 100 \text{ cm}^3/\text{s}$ was approximately 1/9-th as small as employed by Kawakami *et al.*⁹⁾ ($Q_g = 860 \text{ cm}^3/\text{s}$), the present measured values of α on the bath centerline were much larger than those measured by them. For example, the present measured value of α on the bath centerline was about 20% at $z = 55$ mm, while the value measured by Kawakami *et al.* was about 4% at $z = 50$ mm. Agreement between the measured values and the empirical correlation of the present authors was very good in the axial region of $\alpha \leq 50\%$, i.e., for $z \geq 35$ mm.

Figure 11 plots the radial distributions of the bubble frequency f_B . As z increased, the measured values of f_B obtained near the centerline of the bath became a little smaller. The difference between the measured values and the empirical correlation is significant near the nozzle exit but it is negligible for $z \geq 55$ mm.

As mentioned above, the mean bubble diameter $\bar{d}_B$ is about 15 mm, and hence the axial position of $z = 15$ mm is located near the edge of the bubble formation region. Assuming that bubbles are spherical in shape, have the same diameter, and rise straightly in the axial direction, the bubble frequency f_B at $z = 15$ mm would not change in the radial direction. But the experimental results show that f_B decreases clearly in the radial direction. The reason why f_B has a radial profile at $z = 15$ mm can be explained as follows. Bubbles formed at the nozzle exit does not have the same size⁸⁾ and they are not spherical in shape. In addition, bubbles are not axisymmetrical with

Fig. 12. Radial profiles of mean bubble rising velocity $\bar{u}_B$ at different axial positions in the molten iron bath with bottom blowing (1250°C).

Fig. 13. Radial profiles of mean bubble diameter $\bar{d}_B$ at different axial positions in the molten iron bath with bottom blowing (1250°C).

respect to the nozzle axis and depart from the nozzle while slightly oscillating in the radial direction.

The radial distributions of the mean bubble rising velocity $\bar{u}_B$ at the four axial positions are shown in Fig. 12. Change in the measured value of $\bar{u}_B$ in the radial direction was very small at each axial position except $z = 35$ mm. The measured value of $\bar{u}_B$ increased as z increased from $z = 15$ mm and almost approached the predicted value⁴⁾ at $z = 75$ mm.

The radial distributions of the mean bubble diameter $\bar{d}_B$ plotted in Fig. 13 indicate that $\bar{d}_B$ is almost uniform in the radial direction at axial positions except $z = 15$ mm. The measured values were smaller than the predicted value of Sano *et al.*⁷⁾ everywhere in the bath.

If each bubble is spherical in shape and rises straightly in the axial direction, the bubble chord length $\bar{L}_B$ measured using a very fine electrode needle would become

Table 1. Comparison between injected Ar flow rate $Q_{g,in}$ and calculated one $Q_{g,cal}$ from measured α and $\bar{u}_{B,cl}$ values in molten iron bath at 1250°C.

	$Q_{g,in}$ (cm ³ /s)	$Q_{g,cal}$ (cm ³ /s)	$Q_{g,in}$ (cm ³ /s)	$Q_{g,cal}$ (cm ³ /s)
$z = 15$ mm	50	22.2	100	28.7
$z = 35$ mm	50	61.3	100	77.1
$z = 55$ mm	50	65.3	100	90.2
$z = 75$ mm	50	59.7	100	77.8

gradually small as the radial measurement position departs from the bath centerline. As a result, the radial distribution of $\bar{d}_B$ would clearly changes in the radial direction. The fact that the radial distributions of $\bar{d}_B$ at $z = 55$ and 75 mm are almost uniform might be caused mainly because bubbles rise in the bath along zig-zag paths.

5. Comparison between the Injected Gas Flow Rate $Q_{g,in}$ and the Calculated Gas Flow Rate $Q_{g,cal}$ from Measured Values of Gas Holdup and Bubble Rising Velocity

Table 1 shows comparisons between the Ar gas flow rate $Q_{g,in}$ injected through a single-hole nozzle and the calculated one $Q_{g,cal}$ ($= \int_0^\infty 2\pi r \cdot \alpha dr \cdot \bar{u}_{B,cl}$), where the measured values are substituted for α and $\bar{u}_{B,cl}$. Since $\bar{u}_B$ remained unchanged in the radial direction, its centerline value $\bar{u}_{B,cl}$ was used for simplicity. In spite of very short measurement time, the calculated value $Q_{g,cal}$ at every axial position except for $z = 15$ mm agreed satisfactorily with the injected value $Q_{g,in}$ for each Ar gas flow rate. Even for aqueous systems, the degree of agreement was almost the same as observed here. At $z = 15$ mm, on the other hand, $Q_{g,cal}$ was much smaller than $Q_{g,in}$. As this axial position is located near the edge of the bubble formation region, the measured bubble rising velocity does not represent the real bubble rising velocity but a some mixture of the rising velocity and the expanding velocity of the bubble surface. This is the main reason for the significant difference between $Q_{g,in}$ and $Q_{g,cal}$ at $z = 15$ mm.

6. Conclusions

We developed a new electro-resistivity probe being

able to continuously measure bubble characteristics in a molten iron bath at 1250°C, which was agitated by Ar gas injection, over two hours. Measurements were made for the molten iron bath at 1250°C, and the results were summarized as follows:

(1) The axial and radial distributions of gas holdup α , bubble frequency f_B , mean bubble rising velocity $\bar{u}_B$ and mean bubble diameter $\bar{d}_B$ were measured in the molten iron bath at 1250°C for two Ar gas flow rates: $Q_g = 50$ cm³/s and $Q_g = 100$ cm³/s. The radial distributions of α and f_B followed the Gaussian distribution, while $\bar{u}_B$ and $\bar{d}_B$ almost unchanged in the radial direction.

(2) Empirical correlations⁴⁾ of α , f_B and $\bar{u}_B$ derived by the present authors based upon cold model experiments could reasonably approximate their respective measured values located in the region far from the nozzle exit. The present experimental results differed significantly from those by Kawakami *et al.*⁹⁾

(3) The present measured values of mean bubble diameter $\bar{d}_B$ were smaller than predicted values by Sano *et al.*⁷⁾ and Irons *et al.*⁸⁾

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