1. Introduction

A lot of efforts have been devoted to generate small bubbles in molten metal baths to enhance mass transfer and metallurgical reactions between the bubbles and molten metal.\footnote{1–4} Small bubbles however are often trapped in the molten metal after materials processing operations, and they sometimes significantly lower the quality of the products. Such a situation is typically observed in the continuous casting process.\footnote{5} At present, it is rather difficult to remove small bubbles because the buoyancy force acting on them is very small.

A variety of methods have been proposed to remove small bubbles from gas and liquid mixtures.\footnote{6–14} For example, Inoue et al.\footnote{15} and Mizuno et al.\footnote{16} proposed a bubble removal method by focusing on the fact that small bubbles in a water–air two-phase flow in a pipe of poor wettability are likely to attach to the inner wall of the pipe. Accordingly, bubbles in a molten metal bath can also be removed by trailing a solid body of poor wettability behind the cylinder because disintegration of bubbles took place around the cylinder. The mean bubble rising velocity also became very low behind the cylinder. The horizontal spreading of the bubbling jet was significantly suppressed by the cylinder.

2. Experimental Apparatus and Procedure

Figure 1 shows a schematic of the experimental apparatus. The diameter, $D$, and the height, $H$, of the vessel are 0.200 m and 0.400 m, respectively. Water was injected through a centric bottom nozzle of an inner diameter, $d_{ni}$, of 0.0020 m. Measurements were carried out at three gas flow rates;
$Q_g = 10.0 \times 10^{-6} \text{m}^3/\text{s}$, $41.4 \times 10^{-6} \text{m}^3/\text{s}$, and $100 \times 10^{-6} \text{m}^3/\text{s}$. Three circular cylinders made of aluminum were used. Their diameters are $D_c = 0.015 \text{m}$, $0.020 \text{m}$, and $0.030 \text{m}$. One of the cylinders was horizontally placed in a vertical water–air bubbling jet generated in the bath. The distance from the nozzle exit to the lower stagnation point of the cylinder was $0.150 \text{m}$. The cylinder was wetted by water, as mentioned earlier. The contact angle was $63^\circ$. The origin of the Cartesian coordinates $(x, y, z)$ was placed on the upper stagnation point of the cylinder. The centerline of the bubbling jet passes through this position and the center of the nozzle exit.

The bubble motions characterized by bubble frequency, $f_B$, gas holdup, $\alpha$, mean bubble rising velocity, $\bar{u}_B$, and mean bubble diameter, $\bar{d}_B$, were measured with a two-needle electroresistivity probe. \[21,22]\] The number of bubbles passing through the needle tip in 1 s is defined as the bubble frequency. The gas holdup is calculated from:

\[\alpha = \frac{\sum t_{Bi}}{t} \times 100 \text{ (%)} \] ..........................(1)

where $t_{Bi}$ is time required for the $i$-th bubble to pass through the needle tip, $t$ is the measurement time (120 s). The mean bubble rising velocity, $\bar{u}_B$, is determined by averaging the bubble rising velocity data obtained in 120 s. The mean bubble diameter, $\bar{d}_B$, is defined by:\[23]\]

\[\bar{d}_B = 1.5L_B \] ..........................(2)

where $L_B$ is the mean chord length which is directly measured with the electroresistivity probe. The axial measurement position ranges from $z=0.010$ to $0.120 \text{m}$.

The axial (vertical) and horizontal velocity components of water flow, $u$ and $v$, were measured using a two-channel laser Doppler velocimeter. Their mean values, $\bar{u}$ and $\bar{v}$, were calculated from the following equations.

\[\bar{u} = \frac{\sum u_i}{N} \] ..........................(3)

\[\bar{v} = \frac{\sum v_i}{N} \] ..........................(4)

where the subscript $i$ denotes the $i$-th digitized datum and $N$ is the sampling number. Velocity measurements were carried out over 300 s. Further details of the measurement methods should be referred to the previous papers.\[21,22,24]\]

### 3. Experimental Results and Discussion

#### 3.1. Gas Holdup, $\alpha$

Figure 2 shows the distributions of gas holdup in the $x$ direction measured at 7 positions behind the cylinder of $D_c = 0.020 \text{m}$. The gas flow rate was $Q_g = 10.0 \times 10^{-6} \text{m}^3/\text{s}$. The distribution of $\alpha$ is approximately symmetrical with respect to the $z$ axis at every axial position. This fact means that the bubbling jet approaching the cylinder is almost evenly divided into two parts by the cylinder. The gas holdup distributions just behind the cylinder ($0.060 \text{m} \leq z$) have two peaks. As the axial distance, $z$, increases, the horizontal distance between the two peaks becomes small. When $z$ exceeds $z = 0.080 \text{m}$, the two peaks disappear and the $\alpha$ distribution has a single peak. Such a transitional phenomenon was caused through the Coanda effect, as mentioned in the previous study.\[25]\] It should be noted that two parts of a bubbling jet separated by the cylinder merge again into a single bubbling jet but each bubble hardly coalesces with another bubble.

Figure 3 shows the distributions of gas holdup, $\alpha$, in the $y$ direction at $x=0$ under the same experimental condition as that for Fig. 2. Every $\alpha$ distribution has a mild, single peak. The width of the bubbling jet hardly changes in the axial direction.
Figure 4 shows the half-value radius of the distribution of gas holdup, \( a \), in the \( x \) direction. The half-value radius, \( b_a \), is defined as the distance from the \( z \) axis to the position at which \( a \) shows a half of the peak value, as shown in the upper part of Fig. 4. The measured values of \( b_a \) are slightly dependent on the gas flow rate, \( Q_g \), under the conditions considered. In addition, the \( b_a \) values remain nearly constant in the \( z \) direction. Bubbles rising behind the cylinder are forced to move inward, \( i.e. \), to the \( z \)-axis due to the Coanda effect. At the same time, they are also forced to move outward due to turbulent diffusion, because the bubbling jet is still highly turbulent behind the cylinder. The fact that \( b_a \) is hardly dependent on \( z \) just behind the cylinder can be explained by balance of these two forces acting on the bubbles. When \( z \) is further increased, \( b_a \) would increase, as the turbulent diffusion becomes to play an essential role. If the cylinder is removed, \( b_a \) for \( Q_g = 10 \times 10^{-6} \) \( m^3/s \) and \( 100 \times 10^{-6} \) \( m^3/s \) would increase in the axial direction along the lines shown in Fig. 4. No empirical equation however is available for \( Q_g = 10 \times 10^{-6} \) \( m^3/s \). The lines can be calculated from the following empirical equation derived for the buoyancy region in the bubbling jet.22)

\[
b_a = b_a(z_{n5}) = 1.6(Q_g^2/g)^{1/5} \tag{6}
\]

\[
z_{n5} = 17(Q_g^2/g)^{1/5} \tag{7}
\]

where \( z_{n5} \) is the axial distance measured from the nozzle exit which \( a_{cl} \) is 5 \%, and \( g \) is the acceleration due to gravity. It is evident that the width of the bubbling jet in the \( x \) direction can be controlled by placing a cylinder in the bubbling jet.

3.2. Mean Bubble Rising Velocity, \( \bar{u}_B \)

Figure 5 shows the measured values of the mean bubble rising velocity, \( \bar{u}_B \), for the different three \( D_c \) values. The solid line was calculated from an empirical equation of \( \bar{u}_B \) derived by Castello-Branco et al.26) for a bubbling jet in the absence of a circular cylinder.

\[
\bar{u}_B = \left( \frac{\rho_g}{\rho_l} \right)^{0.4} Q_g^{0.2} = 1.60(z_{n}/z_{m0})^{-2.04} + 1.82(z_{n}/z_{m0})^{-0.08} \quad (z_{n}/z_{m0} > 0.6) \quad \tag{8}
\]

\[
z_{m0} = 6.8d_{n0} Fr_{m}^{0.272} \tag{9}
\]

\[
Fr_m = \rho_l Q_g^{2/3} \left( \rho_g \theta_{m0} \right) \tag{10}
\]

where \( z_{m0} \) is the distance from the nozzle exit to the position at which \( \alpha_{cl} \) is 50 \%, \( Fr_m \) is the modified Froude number, \( \rho_l \)}
is the density of air, and \( \rho_1 \) is the density of water. The presently measured \( \bar{u}_B \) value is much different from the calculated value. Consequently, the motions of rising bubbles are significantly suppressed by the cylinder. This is mainly because most bubbles approaching the cylinder collide to the lower part of the cylinder, and, accordingly, their vertical motions are suppressed there. It is difficult at present to quantitatively discuss the relationship between the mean bubble rising velocity and the cylinder diameter because of large scatter of data points. Further discussion should be given after carrying out experiments over much more measurement time.

Figure 6 shows the measured values of \( \bar{u}_B \) for three different gas flow rate values. The cylinder diameter, \( D_c \), is 0.020 m. Three kinds of lines denote the predicted values based on the empirical equation derived by Castello-Branco et al.\textsuperscript{26} As the gas flow rate, \( Q_g \), increases, the mean bubble rising velocity, \( \bar{u}_B \), becomes large but is smaller than the calculated value for a bubbling jet in the absence of the cylinder.

### 3.3. Mean Bubble Diameter, \( \bar{d}_B \)

The mean bubble diameter, \( \bar{d}_B \), shown in Fig. 7 decreases with an increase in the cylinder diameter, \( D_c \). The reason lies in the fact that bubbles colliding to the cylinder disintegrate into smaller bubbles near the lower stagnation point of the cylinder.\textsuperscript{27,28} Namely, bubbles are basically divided into two parts there. In addition, bubbles rising along the cylinder are stretched due to high hydrodynamic shear stress, and, hence, they are further disintegrated into smaller bubbles. The number of bubbles colliding to the cylinder increases as \( D_c \) increases, and, accordingly, much smaller bubbles are generated by a cylinder of a larger diameter. The mean diameter of bubbles behind the cylinder therefore is smaller than that in the region upstream of the cylinder.\textsuperscript{29}

The same situation would be observed for a cylinder of poor wettability. Bubbles smaller than a certain critical diameter however would be trapped on it and remaining bubbles pass around the cylinder. The mean diameter of these bubbles would become smaller than that of bubbles approaching the cylinder. The bubbles passed around the cylinder would be effectively trapped by the other cylinder of poor wettability placed behind the former cylinder.

Anyway, a cylinder of good wettability is useful for generating small bubbles and for collecting them behind it.

### 3.4. Merging Distance, \( H_c \)

Figure 8 shows the measured values of the merging distance of two bubbling jets, \( H_c \). It is defined as the distance from the upper stagnation point of the cylinder to the position at which two peaks on the gas holdup distribution in the \( x \) direction disappear and a single peak appears. The presently obtained merging distance denoted by open symbols decreases gradually with an increase in the gas flow rate, \( Q_g \). This is because the Coanda effect becomes more appreciable behind the cylinder with \( Q_g \). The merging distance agrees approximately with the measured values for a bubbling jet generated with block nozzles.\textsuperscript{30} Water is difficult to be supplied from the region below the block nozzles.
This situation is similar to the present case. Such similarity appears the main reason for the agreement between the presently obtained $H_c$ values and that for the block nozzles. The solid line denotes the following equation.\footnote{31) $H_c = 6.2L_{H}$..................(11)}

where $L_{H}$ is the distance between two nozzles. In calculating $H_c$, the cylinder diameter, $D_c$, was substituted into $L_{H}$ in Eq. (11). This equation overestimates the $H_c$ values behind the circular cylinder.

3.5. Velocity Vectors

Figure 9 shows the velocity vectors of water flow behind the cylinder of $D_c = 0.020$ m. All the vectors are directed toward the $z$ axis, i.e., inward. The same was true for the remaining two cylinders. This situation is caused by the Coanda effect. Such a phenomenon never occurs in the absence of bubbles.\footnote{20)}

3.6. Axial and Horizontal Mean Velocity Components, $\bar{u}$ and $\bar{v}$

Figures 10 and 11 show the vertical and horizontal mean velocity components of water flow, $\bar{u}$ and $\bar{v}$, measured at two axial positions, $z = 0.010$ m and 0.040 m. The solid symbols were obtained for a bubbling jet generated by injecting gas through a porous nozzle.\footnote{20)} The mean bubble diameter, $d_{B}$, was approximately 0.003 m for the porous nozzle, while it was approximately 0.010 m in this case. The measured values of $\bar{u}$ and $\bar{v}$ for the porous nozzle are in good agreement with their respective measured values for the single-hole nozzle, regardless of the mean bubble diameter. The authors reported previously that the $\bar{u}$ distributions in bubbling jets are hardly affected by the mean bubble diameter when the gas flow rate is fixed.\footnote{22)} Accordingly, the same conclusion was derived for the $\bar{u}$ and $\bar{v}$ distributions in the bubbling jet region behind the circular cylinder. The two peaks appearing on the $\bar{u}$ distribution approach each other as $z$ increases.

The bubble Reynolds number, $Re_B$, is defined by

$Re_B = \frac{u_d d_B}{\nu}$..................(12)

$u_d = \bar{u} - \bar{v}$..................(13)

where $u_d$ is the slip velocity and $\nu$ is the kinematic viscosi-
values obtained in the present study. This situation is caused through the Coanda effect. Accordingly, the horizontal width of a bubbling jet can be controlled by placing a circular cylinder in it.

(2) The merging distance, \( H_c \), behind the cylinder is in good agreement with that derived for two bubbling jets generated using block nozzles.

(3) Bubbles colliding to the cylinder disintegrate into smaller bubbles near the lower stagnation point of the cylinder. Also, the bubbles thus disintegrated are further disintegrated into much smaller bubbles while they pass along the cylinder due to hydrodynamic shear stress acting on them. The mean diameter of bubbles behind the cylinder therefore became small compared to that beneath the cylinder.

(4) The liquid flow characteristics behind a circular cylinder placed horizontally in a bubbling jet generated with a single-hole nozzle were in good agreement with those in a bubbling jet generated with a porous nozzle. The mean bubble diameter was much larger in the former case than in the latter case. The mean bubble diameter hardly affected the liquid flow characteristics behind the cylinder under the condition that the wake of bubbles approaching the cylinder was turbulent.

**Nomenclature**

- \( H_c \): Merging distance of bubbling jets (m)
- \( D_c \): Cylinder diameter (m)
- \( d_{in} \): Inner diameter of nozzle (m)
- \( D \): Vessel diameter (m)
- \( g \): Acceleration due to gravity (m/s²)
- \( H_b \): Bath depth (m)
- \( H \): Vessel height (m)
- \( Q_g \): Gas flow rate (m³/s)
- \( L_{dist} \): Distance between two nozzles (m)
- \( x, y, z \): Cartesian coordinates (m)
- \( u, v \): Velocity components in the \( z \) and \( x \) directions (m/s)
- \( \bar{u}, \bar{v} \): Mean values of \( u \) and \( v \) (m/s)
- \( \alpha \): Gas holdup (%)

**REFERENCES**

1. H. Yamamura, Y. Ueshima, Y. Mizukami, K. Amada, K. Misawa and K. Takase: CAMP-ISIJ, 10 (1997), 137.
2. M. Iguchi, Y. Teranishi and S. Yokoya: Metall. Mater. Trans. B, 29B (1998), 1219.
3. S. Yokoya, S. Takagi, M. Iguchi, K. Marukawa and S. Hara: ISIJ Int., 40 (2000), 572.
4. K. Okumura and M. Sano: ISIJ Int., 41 (2001), No. 3, 234.
5. JSPS: Inclusions in Steel, 19th Committee of JSPS, JSPS, Tokyo, (1984).
6. H. Kamimura, S. Yoshihara and H. Azuma: J. Jpn. Soc. Microgravity Application, 10 (1993), 129.
7. O. Mochizuki: Proc. 5th Symp. on Short Period Microgravity Application, Hokkaido Microgravity Society, Sapporo, (1996), 27.
8. Y. Ogawa and N. Tokumitsu: Proc. 6th Int. Iron and Steel Cong., ISIJ, Tokyo, (1990), 147.
9. Jpn. Soc. Microgravity Application, Frontiers in Experiments in Space, B-1135, (1996), 219.
10. H. Azuma, S. Yoshiwara and S. Ogwara: Proc. 27th Symp. on Science and Technology in Space, National Aerospace Laboratory, Kanagawa, (1983), 182.
11. R. Imai and T. Yano: Preprint of Jpn. Soc. Mech. Eng., No. 930-9 (1993), 388; Trans. JSME, 60 (1994), 3979.
12. T. Okusawa, Y. Kojima, K. Tsibouchi, Y. Takagi and T. Hamano: Trans. JSME, (C), 58 (1992), 3543.
13) N. Wakayama: Development of High Temperature Fluid Flow Technologies in Microgravity, NEDO-ITK-9507, (1996), 99.
14) T. Okusawa, K. Tsubouchi, Y. Kojima, Y. Takagi, A. Ashida and T. Hamano: Space '92, JSUP, Tokyo, (1992), 115.
15) T. Inoue, M. Iguchi and Y. Mizuno: Proc. 1st Jpn. Soc. Multiphase Flow Conf., Jpn. Soc. Multiphase Flow, Osaka, (2000), 241.
16) Y. Mizuno, T. Inoue, and M. Iguchi: Proc. 3rd Pacific Symp. on Flow Visualization and Image Processing, Outrigger Wailea Resort, Pacific Center of Thermal-Fluid Eng., Hawaii, (2001).
17) Y. Mizuno, T. Shimizu, N. Sonoyama and M. Iguchi: Jpn. J. Multiphase Flow, 14 (2000), 166.
18) Y. Mizuno and M. Iguchi: ISIJ Int., 41 (2001), Suppl., S56.
19) Y. Mizuno, T. Yamashita, M. Iguchi, and Z. Morita: Proc. 2nd Int. Cong. on Sci. and Tech. of Steelmaking, University of Wales, Swansea, (2001), 513.
20) T. Yamashita, Y. Mizuno and M. Iguchi: Proc. JSMF Annual Meeting 2001, Jpn. Soc. Multiphase Flow, Osaka, (2001), 17.
21) M. Iguchi, H. Takeuchi and Z. Morita: ISIJ Int., 31 (1991), No. 3, 246.
22) M. Iguchi, K. Nozawa, H. Tomida and Z. Morita: ISIJ Int., 32 (1992), No. 6, 747.
23) M. Kawakami, N. Tomimoto and K. Ito: Tetsu-to-Hagané, 68 (1982), No. 7, 774.
24) M. Iguchi, T. Kondoh and T. Uemura: Int. J Multiphase Flow, 20 (1994), 753.
25) K. Sasaki and M. Iguchi: Tetsu-to-Hagané, 85 (1999), No. 6, 432.
26) M. A. S. C. Castello-Branco and K. Schwerdtfeger: Metall. Mater. Trans. B, 25B (1994), 359.
27) K. Ito and M. Tokuda: Tetsu-to-Hagané, 76 (1990), No. 12, 2124.
28) K. Ito and M. Tokuda: Tetsu-to-Hagané, 76 (1990), No. 12, 2131.
29) M. Iguchi, H. Ueda and T. Uemura: Int. J. Multiphase Flow, 21 (1995), No. 5, 861.
30) K. Sasaki and M. Iguchi: Tetsu-to-Hagané, 88 (2002) No. 6, 292.
31) M. Iguchi, K. Takahashi and H. Kiuchi: ISIJ Int., 37 (1999), 1311.
32) G. Hetroni: Int. J Multiphase Flow, 15 (1989), 735.
33) S. Takeli and W. H. C. Maxwell: J. Waterway, Port Coastal and Ocean Div., ASCE, 106 (1980), 49.
34) M. Iguchi, Z. Morita, H. Tokunaga, H. Tatemichi, Y. Sakamoto and S. Takagi: ISIJ Int., 34 (1994), No. 4, 322.
35) M. Iguchi, T. Kondoh, Z. Morita, K. Nakajima, K. Hanazaki, T. Uemura and F. Yamamoto: Metall. Mater. Trans. B, 26B (1995), 241.