Formation of Fine Bubble through Swirling Motion of Liquid Metal in the Metallurgical Container

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In pyrometallurgical processes, creation of gas-dispersed metal system is required to promote an interfacial reaction rate at a gas-liquid metal boundary, as well as to remove non-metallic inclusions in a bulk metal. We found that fine gas bubbles penetrated easily from a container wall to a mercury bath by addition of the swirling motion which created a centrifugal force. Measured radius of bubbles in a metal bath, $B$ is in good accordance with that calculated by the following equation; $B=\left(\frac{1}{2}\right)^{1/3}\left(\frac{1}{w}\right)^{1/2}\left(\frac{2R_s}{r}\right)^{1/2}$: $w$: tangential velocity, $R$: radius of container, $s$: surface tension of molten steel, $r$: density of molten steel. In the system, injection pressure for penetration of bubbles in the metal bath is much lower than that of conventional injection process by tuyeres and lances.

KEY WORDS: fine bubble; centrifugal force; swirling flow; surface tension; reactor; injection pressure.

1. Introduction

Recently, with increasing requirement of high quality metal product, metal refining processes have become increasingly important. In the refining processes, gas injection has been developed to enhance mixing, homogenize temperature, and remove dissolved impurity from the molten metals. Wei et al.1) have demonstrated through a cold model study that when solid particles are not wetted with liquid, they can be captured by gas bubbles and floated up to the free surface. Solid inclusions such as alumina and silica are not wetted with molten steel and therefore are considered to be removed by attachment to gas bubbles. Actually, it is well known that Ar bubbles injected into the steel bath can trap non-metallic inclusions such as alumina and silica and remove them. The development of these processes has been focused on achieving two conditions: generation of fine bubbles and chance for both bubble and inclusion to meet with each other. Fine bubbles provide a large gas/liquid interfacial area, and chance for both bubble and inclusion to meet with each other enhances the efficiency of impurity removal.

Bubbles generated by gas injection with conventional tuyeres and lances are typically 20 mm in diameter.2) It has been considered to be difficult to create a fine bubble. Recently, Yamamura et al. have tried to create fine bubbles through the shearing stress near the wall and succeeded in making considerable fine bubbles.3,4) On the other hand, it may be possible to efficiently remove inclusions through a bubble accumulated zone (bubble curtain) extending from the wall to the central part of the nozzle, created by swirling motion imposed on the flow in an immersion nozzle.5) Therefore, if fine bubbles can be produced, it is anticipated that the bubble curtain created by the swirling flow in the nozzle works to effectively remove the inclusions in the bulk molten steel in the nozzle.

The aim of this work is to develop a novel process to make a fine bubble easily through the difference of centrifugal forces near the container wall, using swirling motion in the container.

2. Experimental Apparatus

Figure 1 shows a schematic of the experimental apparatus for investigating effects on the formation of fine bubbles through swirling flow. The container 1 containing bulk mercury rotates at a rotation speed from 0 to 2 900 rpm. The bulk mercury contained in the stationary container 2 having an injection nozzle 3 is driven tangentially by the container 1. The inner diameter of the nozzle 3 is 0.5 mm. The transparent acrylic pipe with the water jacket 4, namely the water container, for observing the appearance of bubble is set on the upper part of the container 2. Taking both a front and side picture of a rising bubble in the transparent acrylic pipe with the water jacket 4 using a video camera, the volume of a bubble $v$ and the diameter of the bubble $D$ are estimated as follows:

$$v=\frac{\pi BDpH}{6}$$

$$D=\left(\frac{BDpH}{3}\right)^{1/3}$$
where $B$ is the width of the bubble, $Dp$ is the depth of the bubble and $H$ is the height of the bubble, as shown in Fig. 2.

3. Results of Mercury Test

The radial profile of the tangential velocity on the same axial position as the injection nozzle in Fig. 1, calculated under the laminar flow and VOF model with the Fluent code, is shown in Fig. 3. The tangential velocity increases with increasing the radial distance from the axis to the wall, that is, it shows a kind of forced vortex behavior. Here, the tangential velocity is defined as the maximum tangential velocity near the tip of the injection nozzle shown in Fig. 1, as shown in Fig. 3.

The profile of the boundary surface between water and mercury at the revolution speed of the container, 2000 rpm (=tangential velocity near the tip of nozzle, 1 m/s) is shown in Fig. 4. The calculated and experimental results fairly coincide with each other. The situations of rising bubbles in the water container for a case of the tangential velocity less than 0.8 m/s, i.e., revolution velocity of the container, 1500 rpm, observed with a space of 90° are shown in Figs. 5(a) and 5(b), respectively. The bubbles can not penetrate through the bulk mercury and then are rising along the inner wall of the container in Fig. 1. On the other hand, over the tangential velocity near the tip of the injection nozzle, 0.8 m/s, bubbles after passing through the mercury due to the centrifugal force acting on the bubbles by the swirling flow, rise along the center line of the water container as shown in Figs. 6(a) and 6(b).

Figure 7 shows a relationship between the tangential velocity near the tip of the injection nozzle (namely, tangential velocity) and the volume efficiency of bubbles penetrated into the bulk mercury in the container (namely, (bubble volume rate penetrated into bulk mercury, m$^3$/s)/(air volume rate injected from the injection nozzle, m$^3$/s)×100%). This efficiency abruptly rises from 0, over the tangential velocity of 0.8 m/s, and then increases with increasing the tangential velocity. Such a tendency seems to be ob-
tained efficiently because the centrifugal forces acting on the bubbles increase with an increase in the tangential velocity.

A correlation between the injected air flow rate and the volume efficiency of penatrated bubbles is shown in Fig. 7. The volume efficiency of bubbles penetrated into the bulk mercury increases with an increase in the injected air flow rate from the injection nozzle.

Figure 9 shows the injection pressure with various tangential velocities under the injected flow rate of 0.53 cm$^3$/s through the injection nozzle. The injection pressure increases with the increasing tangential velocity. It was found that because the height of mercury near the wall of the containers ① and ② in Fig. 1 increases with increasing tangential velocity in the containers ① and ②, it is necessary to apply higher injection pressure in order to penetrate bubbles through the bulk mercury. The relationship between the flow rate injected from the injection nozzle and the bubble diameter penetrated into the bulk mercury in the container is shown in Fig. 10 under the tangential velocity of 1.15 m/s (2 500 rpm). The number for various diameters of bubbles with increasing the injected flow rate from 0.26 cm$^3$/s to 0.79 cm$^3$/s are represented in Fig. 11, corresponding to Fig. 10. Figure 12 shows the relationship between the tangential velocity and the penetrated bubble diameter.

The number for various penetrated diameters of bubbles are shown for the various tangential velocities corresponding to Fig. 12, as shown in Fig. 13. The observed bubble sizes are in the range 1.5 to 6 mm in diameter. However, the number of bubbles such as 1.5 or 2.5 mm in diameter increases with increasing the tangential velocity from 0.8 m/s to 1.15 m/s.

The number and range of larger diameter bubbles increase with increasing the injected flow rate. However, the critical diameter 1.5 mm always exists in the various injected flow rates at the tangential velocity 1.15 m/s. Accordingly, it seems that the bubbles of critical diameter 1.5 mm exist despite of various injected flow rates and coalesce into the bubbles of larger diameters with increasing the injected flow rate, because the rate of bubble generation increases proportionally with the increasing injected flow rate.

Figure 14 shows the relationship between the injection pressure and the flow rate injected into the bulk mercury. The injection pressure increases with increasing the injected flow rate.
Therefore, it was found that there is an optimum injection pressure to create a bubble-diameter as small as possible.

4. Discussion

From the above-mentioned experimental results, bubbles begin to abruptly penetrate into the bulk mercury over the tangential velocity 0.8 m/s under the injection flow rate of 0.53 cm³/s, and the critical diameter of the bubbles penetrated seems to be dependent on the tangential velocity. Namely, it seems that the penetrated fine bubbles may be produced from the balance of centrifugal force and surface-tension force acting on the bubbles as follows.

The mechanism of bubble generation will be explained using Figs. 15 and 16. The shape of a bubble is assumed to be spherical. The difference of pressure near the wall of the container shown in the Figures can be obtained through the law of momentum as follows;

\[ \rho \Delta R (R\omega)^2 (\sin(\theta/2) - \sin(-\theta/2)) = R\theta \Delta p \] ..........(1)

Assuming \( \theta \) is very small, Eq. (1) reduces to

\[ \Delta p = \frac{\rho \Delta R (R\omega)^2}{R} \] ..........(2)

where, \( \omega \) : Angular velocity of the bulk fluid around the container axis.
If the hemisphere having radius \( b \) (Eq. (6)) results into a sphere just after breaking away from the wall of the container, the critical radius of the sphere \( B \) is assumed to be shown as follows:

\[
(4/3)\pi B^3 = (2/3)\pi b^3 \quad \text{..........................(7)}
\]

\[
B = (1/2)^{1/3}b \quad \text{..........................(8)}
\]

Accordingly,

\[
B = (1/2)^{1/3} \left( \frac{1}{w} \sqrt{\frac{2R\sigma}{\rho}} \right) \quad \text{..........................(9)}
\]

The transport properties used for water, mercury and molten steel are shown in Table 1. Figure 17 shows the calculated (Eq. (9)) and experimental bubble sizes in critical diameter for various tangential velocities. Both the calculated and experimental results for the case of mercury considerably coincide with each other. It was found that with an increase in the centrifugal force acting on the bubble induced by imparting a swirling motion in the liquid, fine bubbles can be produced, and its critical bubble size is to be represented in Eq. (9). Moreover, a calculated bubble size in the critical diameter for the molten steel is shown for the various tangential velocities in Fig. 17. The bubble-size in the critical diameter for the molten steel is cleared to be two times as large as that for the mercury at the same tangential velocity, because the surface tension of the molten steel is larger than that of mercury but the density of the molten steel is smaller than that of the mercury, as shown in Table 1.

5. Conclusions

The following results were obtained with imparting a swirling flow in the container.

1. With an increase in the centrifugal force induced by imparting a swirling motion in the liquid, fine bubbles were accelerated to produce, and obtained bubble sizes were from 1.5 to 6 mm in diameter, i.e., critical diameters of the bubbles were in a range of 1.5 to 2.5 mm. An analytical equation for the critical radius of the bubble is as follows;

\[
R : \text{Inner radius of container} \\
\Delta p: \text{Difference of pressure acting on the bubble} \\
w: \text{Tangential velocity near the inner wall of the container} (w = R\omega) \\
\rho: \text{Density of liquid} \\
b: \text{Radius of hemispherical bubble} \\
\sigma: \text{Surface tension of the bulk liquid}
\]

Assuming boldly that the pressure-difference acting on around the hemispherical bubble is

\[
\Delta p = \frac{\rho (R\omega)^2 b}{R} \quad \text{..........................(3)}
\]

A force balance between \( \pi b^2 \Delta p \) and the surface tension force is given by

\[
\pi b^2 \Delta p = 2\pi b\sigma \quad \text{..........................(4)}
\]

and \( w \) is expressed by

\[
w = R\omega \quad \text{..........................(5)}
\]

The radius of a hemispherical bubble \( b \) is derived from Eqs. (3) to (5);

\[
b = \frac{1}{w} \sqrt{\frac{2R\sigma}{\rho}} \quad \text{..........................(6)}
\]
which represents well the re-productivity of the experimental results. This equation means that the diameter of bubbles produced is a function of tangential velocity, radius of container, surface tension and density of molten metal.

(2) The penetrated volume efficiency of bubbles increases with increasing the tangential velocity and injected air flow rate.

(3) The diameter of bubbles decreases with increasing the tangential velocity.

(4) The diameter of bubbles increases with increasing injecting air flow rate (namely, injection pressure).

(5) Injection pressure for penetration of bubbles in the metal bath is much lower than that of conventional injection process by tuyeres and lances.

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REFERENCES

1) P. Wei, K-I. Uemura and S. Koyama: Tetsu-to-Hagané, 78 (1992), 1361.
2) Y. Xie and F. Oeters; ISIJ Int., 32 (1992), 66.
3) H. Yamamura, Y. Kamisima, Y. Minakami, K. Amada, K. Mizawa and K. Takase, CAMP ISIJ, 10 (1997), 137.
4) K. Takase, K. Mizawa, K. Amada, M. Amano, N. Konno, A. Uehara and H. Yamamura, CAMP ISIJ, 10 (1997), 138
5) S. Yokoya, S. Takagi, H. Souma, M. Iguchi, Y. Asako and S. Hara, ISIJ Int., 38 (1998), 1086.
6) Fluent User’s Manual Version 4.4, Fluent-Asia-Pacific, Inc., Tokyo, (1996).