Intensification of Bubble Disintegration and Dispersion by Mechanical Stirring in Gas Injection Refining

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Water model experiments were performed for establishing highly efficient gas injection refining processes. Mechanical stirring was applied to disintegrate the injected bubbles and to disperse them widely in the bath. The bubble disintegration and dispersion were investigated by changing rotation mode (direction of rotation), rotation speed, blade size of the impeller and gas flow rate. Forward rotation of the impeller induced a stable tangential flow and could not disperse bubbles in the bath due to formation of a vortex around the impeller shaft. The tangential flow could be suppressed by forward–interrupt rotation, which could reduce the vortex formation to some degree. However, forward–interrupt rotation could not disperse the bubbles widely in the bath. Forward–reverse rotation could prevent the vortex formation completely and create a strong shear stress field, which intensified the bubble disintegration and dispersion in the bath. Higher impeller rotation speed and larger blade length in forward–reverse rotation could enhance the bubble disintegration and make the dispersed bubbles smaller. The bubble dispersion zone became wider with larger blade length. The bubble size tended to be larger at higher gas flow rates. However, its dependence on the gas flow rate became smaller at higher impeller rotation speed.

KEY WORDS: injection refining; mechanical stirring; gas injection; bubble disintegration; bubble dispersion; water model.

1. Introduction

In many metal refining processes, a great amount of gas is injected into the bath for the purposes of mixing the melt, enhancing the gas-metal reaction (including removal of nonmetallic inclusion) and the slag-metal reaction, and so on. Especially in the case of gas-metal reaction processes, gas injection is very effective for increasing the reaction interfacial area. However the reaction efficiency of the processes is usually very low. The main reason for the low efficiency is that very large bubbles are inevitably formed owing to very high rates of gas injection through a small number of nozzles.

In the chemical industry, many sophisticated devices for small bubble production are used successfully and the gas–liquid contact equipment is being operated effectively. But successful examples of small bubble production are very few in high temperature refining processes. One of the few examples is the use of a high-speed rotating nozzle (spinning nozzle) in degassing of molten aluminum. In another example, an impeller of relatively small blade length and height with a disk on it is used to produce small bubbles. Since the impeller is rotated at a high speed, the bubbles are disintegrated by the shear force acting on them at the edge of the disk. Forward–reverse rotation can make the bath surface calm and prevent oxide contamination of molten aluminum. Highly clean molten aluminum can be produced by this method.

The sophisticated devices used at room temperature cannot be applied to iron and steel refining operated at high temperatures because refractory materials are used for making the gas injection devices. Since erosion of the refractory materials is very severe at very high rotation speeds, it is difficult to apply the gas injection devices for aluminum refining to iron and steel refining. Mechanical stirring at relatively low rotation speeds, namely KR method, has been used for desulfurization of hot metal. The aim of mechanical stirring is to create a vortex in the bath and to entrain the desulfurization flux powder into the melt. Fundamental water model studies on the powder entrainment are being made by Iguchi et al. In the case of gas injection processes, however, the vortex formation has a fatal effect on bubble dispersion, since injected bubbles gather in the neighbor of the vortex around the impeller shaft and cannot disperse widely in the bath, which results in poor gas–liquid contact or low refining efficiency.

In the present study, water model experiments using mechanical stirring were done for developing highly efficient gas injection refining processes, in which small bubbles are dispersed widely in the bath. The impeller had four blades. The direction of impeller rotation was changed at specified time intervals in the experiments. Three rotation modes were tested; forward rotation, forward–interrupt rotation, and forward–reverse rotation. Air was injected vertically...
downward or horizontally into water through a nozzle at the end of the impeller shaft. The maximum gas flow rate was 4.5 m$^3$/h. A high-speed video camera was used to record the bubble dispersion phenomena in water. The bubble size distribution was measured using an image-processing software. Effects of various operating factors on the bubble disintegration and dispersion were examined.

2. Experimental

The experimental apparatus is shown in Fig. 1. The container of water was made of acrylic resin; the diameter was 0.433 m, and the height 0.51 m. This container size is about one-tenth of the actual hot metal ladle. The present experiments were conducted without installing baffles at the container wall, because they raise the container production and maintenance cost in the actual refining processes. Figure 2 shows a thick four-blade impeller, which can be made of refractory material. This type of impeller is appropriate for metal refining, as is used in the KR method. Three rotation modes of the impeller are named as Mode 1 (forward rotation; conventional way), Mode 2 (forward–interrupt rotation; forward rotation 3 s–interrupt 0.5 s), and Mode 3 (forward–reverse rotation; forward rotation 3 s–reverse rotation 3 s). The impeller rotation speed was varied between 0.83 and 2.5 s$^{-1}$. The nozzle installed at the end of the hollow impeller shaft had four holes whose diameter was 2 mm. Air was injected horizontally into water through the nozzle at a gas flow rate between 2.3 and 4.5 m$^3$/h. The effect of blade size on bubble dispersion was studied under the following condition. The blade lengths were 0.18, 0.22 and 0.26 m, the blade height was 0.05 m, and the blade thickness was 0.04 m.

The behavior of gas injected into water was recorded by a high-speed video camera (500 frame/s), and was input into a computer. The static picture of bubble dispersion was analyzed by an image-processing software to obtain the histogram of bubble size distribution.

3. Experimental Results and Discussion

3.1. Effect of Impeller Rotation Mode on Bubble Disintegration and Dispersion

3.1.1. Relation between Impeller Rotation Mode and Macroscopic and Microscopic Flows in Bath

Bubble disintegration and dispersion are closely related to the macroscopic and microscopic flows in the bath. As shown in Fig. 3, mechanical stirring induces macroscopic flows: tangential flow, radial flow, and circulating flow. These macroscopic flows depend on stirring Reynolds number ($Re=\rho d^2 N/\mu$, $\rho$: liquid density, $d$: impeller blade length, $N$: rotation speed of impeller, $\mu$: liquid viscosity) and control the mixing of the bath. Since no baffle was used in the present experiments, the tangential flow for the impeller rotation of Mode 1 was very strong. In this case, centrifugal force acts on the liquid, and forms a vortex or inverted cone type depression on the water surface. When gas is injected into the bath, centripetal force acts on the dispersed bubbles and draw them to the vortex. Thus the bubbles cannot disperse widely in the bath. In order to operate the gas injection refining process efficiently, we have to suppress the tangential flow or the vortex formation. For this purpose, we adopt two rotation modes: Mode 2 and Mode 3.

Figure 4 shows difference in vortex formation among the rotation modes with gas injection. The impeller rotation speed and the gas flow rate were 2.5 s$^{-1}$ and 4.5 m$^3$/h, respectively. In the case of Mode 1, a strong tangential flow was formed, and a very large vortex was induced, as shown in Fig. 4(a). Figures 4(b) and 4(c) are the pictures for Mode 2 (forward rotation 3 s–interrupt 0.5 s) and Mode 3 (forward rotation 3 s–reverse rotation 3 s). Vortex formation could be prevented to some degree by forward–interrupt rotation and perfectly by forward–reverse rotation. As a result, microscopic or turbulent flow was produced. Hence the impeller rotation of Mode 3 can create a strong shear stress or turbulence field, in which the bubble disintegration and dispersion proceed intensely.
3.1.2. Mode 1 (Forward Rotation)

Figure 5 shows the time series pictures of vortex formation and bubble dispersion before and after initiation of forward rotation. The impeller rotation speed was $2.5 \text{ s}^{-1}$. The air flow rate was 4.5 m$^3$/h. Figure 5(a) displays the bubble dispersion in water before impeller rotation. Since the four-hole nozzle was used and air was injected horizontally, bubbles could disperse partly in the bath. Local bubble dispersion and existence of some large bubbles made the bath surface wavy. Figure 5(b) is the picture at the beginning of rotation. Bubble disintegration proceeded intensely, and small bubbles were dispersed widely in the bath, so that the bath surface became calm. With the lapse of time, however, a vortex was gradually formed, and bubbles gathered around the impeller shaft. At the steady state, a strong stable tangential flow was formed and bubbles could not disperse in the bath.

Conclusively, forward rotation of the impeller requires installation of baffles at the container wall to disturb the tangential flow and to disintegrate and disperse the bubbles in the bath.

3.1.3. Mode 2 (Forward–Interrupt Rotation)

Forward rotation of 3 s alternating with interrupt of 0.5 s was repeated in Mode 2. The other experimental conditions were the same as those of Mode 1. Figures 6(a) and 6(b) are pictures at the beginning of forward rotation and at the end of interrupt, respectively. The macroscopic flow, and the bubble disintegration and dispersion by Mode 2 were unsteady. The bubble disintegration and dispersion were best immediately after switching from interrupt to forward rotation. However it was worse at the end of the interrupt.

If the time of forward rotation were too long or the time of interrupt were too short, the tangential flow and vortex could keep existing. Thus injected bubbles would not be dispersed in the bath. Figure 6(b) indicates that under the present experimental conditions, the interrupt time of 0.5 s is not long enough for complete disappearance of the tangential flow. Consequently the bubble dispersion was not so good even at the beginning of the forward rotation.

3.1.4. Mode 3 (Forward–Reverse Rotation)

Figure 7 shows the bubble dispersion in the bath by Mode 3. In this experiment forward and reverse rotation were repeated alternately every 3 s. The other experimental conditions were the same as those of Modes 1 and 2. Since the shift time of the rotation was short, the vortex hardly formed. No vortex formation is the reason why the bubble disintegration proceeded extremely well with small bubbles dispersing widely in the bath. It is estimated that the tangential flow was almost suppressed and the very high shear
stress field was formed by the forward–reverse rotation.

The picture in Fig. 7 is treated by an image-processing software to obtain the size distribution of bubbles. The result is shown in Fig. 8. Since the container was three dimensional with high bubble density, the measurement error is not small. However, the existence of small bubbles in the bath proves that the forward–reverse rotation is most appropriate for the bubble disintegration and dispersion in the bath.

3.2. Effect of Impeller Rotation Speed on Bubble Disintegration and Dispersion

3.2.1. Mode 1 (Forward Rotation)

The pictures of steady-state bubble dispersion by Mode 1 are shown in Fig. 9. The gas flow rate was 4.5 m$^3$/h. The rotation speeds of the impeller were 0.83, 1.67 and 2.5 s$^{-1}$. At the rotation speed of 0.83 s$^{-1}$, not only small bubbles, but also some very large bubbles are found in the picture. At this rotation speed, the tangential flow was weak, resulting in no clear vortex formation, so that the radial expansion of bubble dispersion was better than those at the other two rotation speeds. The water surface was wavy because large bubbles broke the water surface. As the rotation speed of the impeller increased, the tangential flow became stronger. At the rotation speed of 1.67 s$^{-1}$, a distinct vortex was formed (Fig. 9(b)), and at the rotation speed of 2.5 s$^{-1}$, it became very clear and large (Fig. 9(c)). In the presence of the vortex, the bubbles gather near the vortex, and cannot disperse widely in the bath.

3.2.2. Mode 2 (Forward–Interrupt Rotation)

Figure 10 shows the experimental results for the impeller rotation of Mode 2. The experimental conditions were the same as those in Fig. 9. The pictures were taken during impeller rotation. Large bubbles were found at 50 rpm. At higher rotation speeds, smaller bubbles did...
exist. Particularly at 2.5 s$^{-1}$, very small bubbles could be found around the impeller, but could not disperse widely in the bath owing to the vortex formation. As shown in Fig. 6, the bubble disintegration and dispersion by Mode 2 are highly unsteady. Hence the phenomena depend on the time when the pictures were taken.

3.2.3. Mode 3 (Positive–Reverse Rotation)

Figure 11 shows the pictures for Mode 3. The experimental conditions except the rotation mode were the same as those of Figs. 9 and 10. At 0.83 s$^{-1}$, some large bubbles were found in the bath and the surface was very wavy. At 1.67 and 2.5 s$^{-1}$, many small bubbles were dispersed and the bubble disintegration was remarkably well owing to intense development of the turbulence field. The bubble dispersion was wider at the higher rotation speeds. It is to be noted that with increasing impeller rotation speed, the bath surface became calm and splash formation was reduced. This fact can be explained by the wide dispersion of small bubbles in the bath.

3.3. Effect of Blade Size of Impeller on Bubble Disintegration and Dispersion

Besides by the rotation speed of the impeller, the macroscopic and microscopic flows are influenced strongly by the blade length of the impeller. In order to investigate the effect of the blade length on the bubble disintegration and dispersion, experiments were carried out using impellers of different blade lengths.

The pictures of bubble dispersion are shown in Fig. 12. The forward–reverse impeller rotation can create a stronger turbulence field with larger blade length. Therefore, as the blade length increased, the bubble size decreased to be very small. The small bubbles were dispersed widely in the bath and the bath surface became calm.

3.4. Effect of Gas Flow Rate on Bubble Disintegration

The experimental results of bubble dispersion at different gas flow rates are shown in Fig. 13. The impeller rotation mode and speed were Mode 3 (forward–reverse rotation) and 1.67 s$^{-1}$, respectively. The gas flow rates were 2.3, 3.5 and 4.5 m$^3$/h. The image-processing software is used to obtain the size distribution of bubbles, from which the volume–surface mean bubble diameter can be calculated. The results are plotted against gas flow rate in Fig. 14.

Generally speaking, the size of bubbles in liquid increases with increasing gas flow rate, or more accurately with increasing superficial gas velocity, that is gas flow rate divided by the cross sectional area of gas-liquid two-phase flow zone. This is because bubble coalescence takes place more frequently at higher superficial gas velocity.9) As shown in Fig. 14, however, although the bubble diameter tended to increase with the gas flow rate, the tendency of the increase in bubble diameter became smaller at higher impeller rotation speeds because the strong turbulence field prevents the bubble coalescence.

3.5. Relation between Volume–Surface Mean Bubble Diameter and Reynolds Number

The size of bubbles in the bath under mechanical stirring is dependent on stirring power per unit liquid volume $P_V$. Here, however, Reynolds number is used to correlate the bubble size with the mechanical stirring conditions. In Fig. 15, the volume–surface mean bubble diameter $d_{VS}$ is plotted against Reynolds number under the condition of gas flow rate of 4.5 m$^3$/h. It is clear that the volume–surface mean

![Fig. 11. Effect of impeller rotation speed on bubble dispersion and disintegration by Mode 3.](image1)

![Fig. 12. Effect of blade length on bubble disintegration and dispersion.](image2)
bubble diameter decreases with increasing Reynolds number.

4. Mechanical Stirring for Gas Injection Refining in Iron and Steel Making

The vessel size and operating conditions of the present water model are much different from those of actual plants. In the following, we discuss applicability of the present experimental results to the actual plants.

Since a large quantity of melt is treated in iron and steel making plants, the reactors are very large and the gas flow rates in gas injection refining are very high. The plants have vessel diameters about ten times larger and hence the cross sectional areas about a hundred times larger than the present water model. The gas flow rates in the plants are about 100–1000 times higher than that in the water model, depending on the purpose of the refining.

Here, we take up Mg desulfurization of hot metal for discussion. Hot metal of 300 ton is desulfurized from 300 to 20 ppm in 15 min by Mg injection. For simplicity, all the injected Mg gas is used for desulfurization. Then the required amount of Mg is 63.6 kg. The total volume of the vaporized Mg is 18.5 m³ at 1723 K and 2 atm (nozzle exit), and the Mg flow rate is 739 m³/h, which is about 160 times that of the present water model. The gas flow rates in the plants are about 100–1000 times higher than that in the water model, depending on the purpose of the refining.

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Calderbank obtained a correlation for the volume–surface mean diameter of bubbles $d_{VS}$ in a stirred tank\(^\text{(10)}\)

$$d_{VS}/H^{1/5} = 4.15\left(\frac{\sigma^{1/3}}{P_V^{2/5}}\right)H^{1/2} + 0.09$$

where $\sigma$ is the surface tension of the liquid, and $H$ is the gas holdup. Equation (1) is the original expression, in which the unit of $d_{VS}$ is cm. It is seen that the bubble disintegration due to mechanical stirring is governed by the power consumption per unit liquid volume, $P_V$. The differences in the surface tension and density of liquid should be taken into account in estimating the bubble size in molten iron on the basis of the present water model experiment.

When the input stirring power is consumed in the strong turbulence field, and the geometrical similarity is satisfied, $P_V$ can be expressed as

$$P_V \propto \rho N^2 d^2$$

where $d$ is the blade length. Substituting Eq. (2) into Eq. (1) with some rearrangement gives Eq. (3):

$$d_{VS}/d = 4.15\left(\frac{\sigma^{1/3}}{P_V^{2/5}}\right)H^{1/2} + 0.09/d$$

where $W_e$ is the Weber number ($=\rho N^2 d^2/\sigma$) and the unit of $d$ is the same as that of $d_{VS}$ only in Eq. (3). The same correlation as Eq. (3) with neglect of the second term has been obtained in liquid–liquid systems.\(^\text{(1)}\) Hence it is seen that the disintegration mechanism of bubbles is similar with that of drops. In case that $\sigma/\rho$ of molten iron is 3.5 times that of
water and the blade length in the actual plant is ten times that of water, we obtain the following relation.

\[ \frac{d_{VS,PL}}{d_{VS,W}} = 0.34 \] .............................(4)

where the subscripts Pl and W indicate the actual plant and the water model, respectively. Hence it is estimated that such a large impeller may not be necessary for obtaining the same bubble size in the plants as that in the water model.

5. Conclusion

Water model experiments were undertaken for establishing highly efficient gas injection refining processes. Mechanical stirring was applied to disintegrate the injected bubbles and to disperse them widely in the bath. The direction of impeller rotation or the rotation mode was changed in the experiments: forward rotation, forward–interrupt rotation, and forward–reverse rotation. The main results are summarized as follows:

(1) Forward rotation (Mode 1) induces a stable tangential flow, which leads to formation of a large vortex. As a result, injected bubbles gathers around the impeller shaft, so that they cannot disperse widely in the bath and the gas–liquid contact is worst.

(2) If the direction of impeller rotation is changed before the stable tangential flow or the vortex is formed, the mechanical stirring can create a strong shear stress or turbulence field in the bath, which intensifies the bubble disintegration and dispersion.

(3) Under the present experimental conditions of Mode 2 rotation (forward rotation 3 s–interrupt 0.5 s), the vortex formation cannot be prevented perfectly, so that bubbles cannot be dispersed widely in the bath.

(4) The Mode 3 rotation (forward 3 s–reverse 3 s rotation) can prevent the vortex formation perfectly and disperse small bubbles widely in the bath. The gas–liquid contact of this rotation mode is much better than those of the other two rotation modes.

(5) Higher impeller rotation speed and larger blade length in Mode 3 successfully establish the bubble disintegration and wide dispersion of smaller bubbles in the bath. The bubble size tends to be larger at higher gas flow rates. However, its dependence on the gas flow rate becomes smaller at higher impeller rotation speed.

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