Effect of Flux Dispersion Behavior on Desulfurization of Hot Metal

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In order to improve the efficiency of the desulfurization process utilizing the mechanical stirring method, the effect of flux dispersion on the hot metal desulfurization reaction was investigated in 1/8-scale water model and 70 kg-scale hot metal experiments. Flux dispersion behavior is divided into three stages, i.e., "non-dispersion," "transition," and "complete dispersion." The desulfurization rate increases remarkably from the "non-dispersion" to the "complete dispersion" stage, corresponding to the change in the condition of particle dispersion. The relationship between the impeller position and the vortex depth is defined as the dispersion index, I. When the dispersion index was over 1, complete dispersion occurred in water model experiments, and the apparent rate constant increased remarkably in hot metal experiments. The observed diameter of the desulfurization slag was 1.4 mm, which is in good agreement with the calculated value, 1.55 mm. This means that fine desulfurization flux aggregates immediately after the addition of the flux. In order to increase desulfurization efficiency, it is important to control this particle aggregation.

KEY WORDS: hot metal; desulfurization; mechanical stirring.

1. Introduction

Mechanical stirring has been widely applied to various fields including chemical processes in order to enhance mixing characteristics and reaction efficiency. Mechanical stirring by rotating an impeller is a simple and easy method, and several studies have been reported concerning new applications, such as new designs of blades or baffles.1–5) In the steelmaking process, the mechanical stirring method was applied to the hot metal desulfurization process. Kanbara6) first applied mechanical stirring with impeller rotation to the hot metal desulfurization process in Japan. The mechanical stirring method has been applied to the hot metal desulfurization process due to its simplicity and strong stirring effect.7,8)

Various studies have been carried out in connection with this method with the aim of improving desulfurization efficiency. For example, Ando et al.9) and Kuroyanagi et al.10) evaluated the effect of baffles with a water model and a 30-ton ladle, respectively. Sohn et al.11) reported the effect of baffles with 100 ton-scale mechanical stirring, finding that desulfurization efficiency increased by twice with the baffles. Nakanishi et al.12) confirmed the effect of gas injection from a gate-shaped impeller, and desulfurization efficiency was improved by gas injection in combination with impeller stirring.

The shape of the impeller blade is also important in the mechanical stirring method. Kurokawa et al.13) investigated the effect of a newly-designed blade with a water model and a commercial-scale desulfurization process. Flux dispersion was improved with the new blade.

Basic studies with water models were carried out in order to study the dispersion behavior of low-density particles by mechanical stirring. Nomura et al.14) evaluated the effect of offset agitation in enhancing low-density particle dispersion. An inclined vortex was observed with offset stirring, which resulted in an increase in the vertical flow velocity by generating an asymmetric flow. Mixing behavior was improved by this phenomenon. Okumura et al.15) confirmed the effect of inclined impeller immersion, and found that inclined immersion improved particle dispersion by generating an asymmetric flow pattern.

As reported above, promotion of flux dispersion into hot metal is one of the most important methods to increase desulfurization efficiency. However, the relationship between flux dispersion behavior and the desulfurization reaction has not been sufficiently clarified. Therefore, in this work, 1/8-scale water model and 70 kg-scale hot metal experiments were carried out in order to understand this relationship.

2. Experimental Procedure

2.1. Water Model Experiment

Flux dispersion behavior with impeller stirring was investigated using a water model. A schematic drawing of the
1/8-scale water model apparatus is shown in Fig. 1.

The apparatus consists of a cylindrical acrylic tank (inner diameter: 523 mm and height: 695 mm (water height: 414 mm)) and an aluminum impeller (diameter: 203 mm, height: 110 mm, and impeller width: 52 mm (4 blades, Angle of blades to the horizontal plane: 90°)). A motor with an inverter controls the rotation speed of the impeller. The immersion depth of the impeller into the water bath is variable. Table 1 summarizes the experimental conditions used in the water model experiment. In this experiment, the rotation speed was changed in the range of 0 to 480 rpm. The impeller immersion depth, defined as the distance from the water surface to the bottom level of the impeller, was set at either 214 mm or 338 mm. The influence of the rotation speed on particle dispersion behavior was investigated. Styrene foam particles (12 g, average diameter: 2 mm, density: 0.03 g/cm³) were added on the water as a simulated flux. Flux dispersion behavior was observed and analyzed using a video camera. The interfacial area between the particles and water was evaluated by photographing and counting the number of the dispersed particles in areas A and B, as shown in Fig. 1.

Table 1. Experimental conditions for water model.

<table>
<thead>
<tr>
<th>Vessel</th>
<th>Height</th>
<th>Diameter</th>
<th>Water Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>695 mm</td>
<td>523 mm</td>
<td>414 mm</td>
</tr>
<tr>
<td>Rotation speed</td>
<td>0 ~ 480 rpm</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Impeller</th>
<th>Height</th>
<th>Diameter</th>
<th>Width</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>110 mm</td>
<td>203 mm</td>
<td>52 mm</td>
</tr>
<tr>
<td>Impeller immersion depth</td>
<td>214 mm, 338 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Particle</td>
<td>Diameter</td>
<td>Density</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.03 g/cm³</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.2. 70 kg-scale Hot Metal Experiment

To investigate the influence of flux dispersion on the desulfurization reaction, 70 kg-scale hot metal experiments with mechanical stirring were performed. The experimental apparatus and conditions are shown in Fig. 2 and Table 2, respectively.

A high frequency induction furnace was used to control the temperature of the hot metal. After adjusting the hot metal temperature to 1573 K and the specified composition of the hot metal, a graphite impeller was positioned at the center of the MgO crucible and immersed into the hot metal. The impeller immersion depth was defined as the distance from the surface of the molten hot metal to the bottom level of the impeller, and was fixed at 150 mm. The rotation speeds were set in the range of 270 – 800 rpm to control the stirring conditions and the vortex shape to be the same as those in the water model experiment. After achieving a preset rotation speed, aluminum ash (50% metallic Al – 25%Al₂O₃ – 5%SiO₂) was added as a deoxidant, and a fine CaO-based flux (CaO – 5%CaF₂, ≤1 mm) was added. It should be noted that, in this paper, "percent" means mass percent unless otherwise stated. Hot metal samples were taken at 1 to 2 min intervals during the experiment. In addition, the vortex height at the wall of the crucible and the vortex depth near the shaft of the impeller were measured with a copper rod (2 mm dia.) and compared with the calculated values.

Table 2. Experimental conditions for 70kg-scale hot metal experiment.

<table>
<thead>
<tr>
<th>Furnace</th>
<th>150 kg IF</th>
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<tbody>
<tr>
<td>ø 250 mm</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Metal</th>
<th>Chemical composition</th>
<th>Fe – 4~5 mass%[C]</th>
</tr>
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<tbody>
<tr>
<td>Weight</td>
<td>70 kg</td>
<td></td>
</tr>
<tr>
<td>Depth</td>
<td>204 mm</td>
<td></td>
</tr>
<tr>
<td>Rotation speed</td>
<td>270 ~ 800 rpm</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Impeller</th>
<th>Height</th>
<th>Diameter</th>
<th>Width</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>80 mm</td>
<td>100 mm</td>
<td>25 mm</td>
</tr>
<tr>
<td>Impeller immersion depth</td>
<td>150 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>1573 K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flux</td>
<td>CaO-5% CaF₂</td>
<td>≤1 mm, 5kg/t</td>
<td></td>
</tr>
<tr>
<td>Al ash (0.3 kg/t)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3. Results and Discussion

3.1. Particle Dispersion Behavior in Water Model

3.1.1. Particle Dispersion Behavior with Impeller Stirring

The typical particle dispersion behavior in the water model is shown in Fig. 3. The vortex depth increases as the rotation speed of the impeller increases. At 160 rpm, particles do not disperse into the water, but simply collect on the water surface. At a higher rotation speed of 240 rpm, the vortex depth reaches the top of the impeller, and particle
dispersion starts. At the maximum rotation speed of 320 rpm, complete dispersion occurs when the bottom of the vortex is deeper than the bottom of the impeller.

Figure 4 shows the case of the impeller immersion depth of 214 mm. The vortex depth increases as the rotation speed increases, and particle dispersion starts when the vortex reaches the top of the impeller, as with the impeller depth of 338 mm. In this case, particle dispersion starts at the rotation speed of 160 rpm, which is smaller than that with the impeller depth of 338 mm (240 rpm), and complete dispersion occurs at the rotation speed of 240 rpm, which is also smaller than that with the impeller depth of 338 mm (320 rpm). However, with the impeller depth of 214 mm, the particles are only dispersed in the upper region of the water bath. On the other hand, with the impeller depth of 338 mm, dispersed particles can be observed in both the upper and lower parts of the bath.

Particle dispersion behavior can be categorized into the following three distinct stages, as shown in Fig. 5.

1. Non-dispersion stage: The vortex depth does not reach the top of the impeller, and no particle dispersion into the water is observed.
2. Transition stage: The vortex depth is at an intermediate vertical position between the top and bottom of the impeller. Particle dispersion starts.
3. Complete dispersion stage: The vortex depth is deeper than the bottom of the impeller. Particles are dispersed throughout the water.

An image analysis was carried out to evaluate the particle ratio in the water as the interfacial area. The number of dispersed particle was counted in the specific areas (A or B) of the water bath described in Fig. 1. The numbers of dispersed particles in the upper area, A, and the lower area, B, are shown in Fig. 6 and Fig. 7 respectively. The number of dispersed particles increased remarkably when the bottom of the vortex was deeper than the bottom of the impeller, as shown in Figs. 3 and 4.

The number of dispersed particles increased in area A when the rotation speed reached a critical value (240 rpm with the impeller depth of 214 mm, 320 rpm with 338 mm). When the impeller depth is shallower (the impeller depth of
214 mm), particle dispersion starts at a lower rotation speed. However, the number of dispersed particles in area B increased only from 1 to 8.4% when complete dispersion occurred.

When the impeller depth is 214 mm, the number of dispersed particles in area A increased remarkably at the rotation speed of 240 rpm, and decreased rapidly at the rotation speed of 320 rpm. This is attributed to the bubble generation in the water, which strain the particle dispersion into the water at the higher rotation speed above 320 rpm, as shown in Fig. 4.

On the other hand, when the impeller depth is deeper (impeller depth of 338 mm), the number of dispersed particles in area B increased remarkably at the rotation speed of 320 rpm, which corresponded to complete dispersion in the case of the impeller depth of 338 mm. This means that a deeper impeller depth is effective for particle dispersion.

Here, the ratio of the vortex depth and the bottom of the impeller is defined as the dispersion index, I,

\[ I = \frac{\text{vortex depth}}{\text{impeller immersion depth}} \]

When the vortex depth is deeper than the bottom of the impeller, the dispersion index is over 1. The relationship between the dispersion index and the number of dispersed particles is shown in Fig. 8. When the dispersion index was over 1, the number of dispersed particles increased remarkably at both impeller immersion depths.

3.1.2. Relationship between Rotation Speed and Vortex Shape

From the results in Sec. 3.1.1, the relationship between the impeller immersion depth and the vortex depth is important for achieving “complete particle dispersion.” Particle dispersion behavior can be estimated by calculating the vortex depth. Equations (1)–(5) were deduced by Nagata et al.\(^\text{16}\) from the viewpoints of the balance of dynamic pressure and centrifugal force and the geometric conditions. The vortex depth, \(\Delta H_1\), and the vortex height, \(\Delta H_2\), generated by impeller stirring can be calculated using these equations.

\[
\Delta H_1 = N^2 \cdot D^2 \cdot \frac{(\pi/30)^2}{4g} \cdot \frac{1/y^2 - \ln(1/y) - 3/4}{1/y^4} \quad \ldots (1)
\]

\[
\Delta H_2 = N^2 \cdot D^2 \cdot \frac{(\pi/30)^2}{4g} \cdot \frac{\ln(1/y) + 1/4}{1/y^4} \quad \ldots (2)
\]

\[
y = \frac{2 \cdot r_c}{D} \quad \ldots (3)
\]

\[
r_c = \frac{d}{2} \cdot 1.23 \cdot \left( \frac{0.57 + 0.35 \cdot \left( \frac{d}{D} \right)}{0.036 \cdot (n_p)^{0.116} \cdot \left( \frac{Re}{10^3 + 1.43 \cdot Re} \right)} \right) \quad \ldots (4)
\]

\[
\text{Re} = \rho \cdot n \cdot d^2 / \mu \quad \ldots (5)
\]

where, \(\Delta H_1\): vortex depth (m), \(\Delta H_2\): vortex height (m), \(D\): diameter of container (m), \(N\): rotation speed (rpm), \(b\): height of impeller (m), \(d\): diameter of impeller (m), \(n\): rotation speed (1/n), \(n_p\): number of blades, \(y\): ratio in radius of cylindrical rotating zone and container (–), \(r_c\): radius of cylindrical rotating zone (m), \(Re\): Reynolds number (–), \(g\): gravitational acceleration (= 9.8 m/s\(^2\)), \(\mu\): viscosity of liquid (Pa·s), \(\rho\): density of liquid (kg/m\(^3\)). The respective signs of the position and the angle are as shown in Fig. 2.

The relationship between rotation speed and vortex depth, \(\Delta H_1\), is shown in Fig. 9. In the water model, \(\Delta H_1\) and \(\Delta H_2\) were measured with a ruler, which was fixed on the outside of the container. The calculated results agreed well with the measured values. In the case of the impeller depth of 214 mm, the experimental vortex depth deviated from the calculated line, and saturated at 260 mm at higher rotation speeds of more than 240 rpm.

From the observation, at higher rotation speeds of more than 240 rpm, the diameter of the vortex exceeds the diameter of the impeller. Therefore, the size of the vortex does not spread even with the higher rotation speeds in the case of the depth of 214 mm.

When the impeller depth was 338 mm, the vortex depth reached the bottom of the container (414 mm) at rotation speeds higher than 320 rpm.

The relationship between the rotation speed and the vor-
The vortex depth, \(\Delta H_1\), and the vortex height, \(\Delta H_2\), is shown in Fig. 10. Again, the calculated results showed good agreement with the measured values, demonstrating that the vortex depth, \(\Delta H_1\), and the vortex height, \(\Delta H_2\), can be calculated using Eqs. (1)–(5).

### 3.2. Relationship between Particle Dispersion and Desulfurization Behavior in 70 kg-scale Hot Metal Experiment

#### 3.2.1. Influence of Rotation Speed

The 70 kg-scale hot metal experiments were carried out in order to investigate the influence of flux dispersion on the desulfurization reaction. The effect of rotation speed on desulfurization behavior is shown in Fig. 11. The desulfurization rate increased with increasing rotation speed. Figure 12 shows the change of \(\log[S]/[S]_0\) as a function of time. Because this relationship is linear, as shown in Fig. 12, the desulfurization rate can be expressed by Eq. (6). The desulfurization rate was evaluated by the apparent rate constant, \(K\). \([S]_0\) is the initial sulfur concentration in hot metal at time \(t=0\), and \([S]_e\) is the equilibrium sulfur concentration, which can be assumed as 0.\(^{15}\)

\[
\frac{d[S]}{dt} = \frac{A k_m}{V} ([S] - [S]_e)
= -K \cdot [S] \quad ([S]_e = 0) \quad \cdots (6)
\]

where, \(A\): surface area, \(k_m\): mass transfer rate in metal \((\text{m/min})\), \(V\): volume of hot metal \((\text{m}^3)\), \(K\): apparent rate constant \((1/\text{min})\).

#### 3.2.2. Vortex Shape and Desulfurization Behavior

The vortex depth, \(\Delta H_1\), and the vortex height, \(\Delta H_2\), were also measured in the hot metal experiment and compared with the calculated results. The observed and calculated vortex depths, as calculated using Eqs. (1)–(5), are shown in Fig. 13. The vortex depth, \(\Delta H_1\), and vortex height, \(\Delta H_2\), increase as the rotation speed increases, and the experimental values are in good agreement with the calculated ones. From these results, the vortex shape of hot metal can be estimated using these equations.

The relationship between the dispersion index, \(I\), and the apparent rate constant, \(K\), is shown in Fig. 14. When the dispersion index is over 1, the apparent rate constant increases remarkably. Therefore, in order to achieve the complete dispersion condition, the vortex depth should be controlled to be deeper than the bottom of the impeller, so that the dispersion index is over 1.

Ishida et al.\(^{18}\) reported that the apparent desulfurization rate constant with flux injection in hot metal increased remarkably when slag entrainment into the hot metal
occurred. This phenomenon is explained by a spike in the interfacial area of the slag in the hot metal. Nakanishi et al.\(^{19}\) reported that the mass transfer coefficients between slag and metal increased greatly with entrainment of \(\beta\)-naphthol (simulating slag) into water (simulating metal).

The operational condition of a commercial-scale desulfurization process is shown in Fig. 14. A high apparent rate constant can be obtained by adjusting the stirring conditions to control the dispersion index to over 1.

### 3.2.3. Relationship between Stirring Energy and Apparent Rate Constant

The stirring energy by mechanical stirring is calculated using the following Eqs. (7)–(12), which were proposed by Nagata et al.\(^{20}\)

\[
P = N_p \cdot \rho \cdot n^3 \cdot d^5 \quad \text{..................(7)}
\]

\[
N_p = \frac{a}{\text{Re}} + B \left( \frac{10^3 + 1.2 \cdot \text{Re}^{0.66}}{10^3 + 3.2 \cdot \text{Re}^{0.66}} \right) \times \left( \frac{Z}{D} \right)^{0.35 + 2b/D} \quad \text{.................(8)}
\]

\[
a = 14 + (2b/D) \times (670 \cdot (d/D - 0.6)^2 + 185) \quad \text{...........(9)}
\]

\[
B = 10^{1.3 - 4(2b/D - 0.5)^2 - 1.14(d/D)} \quad \text{..........(10)}
\]

\[
p = 1.1 + 4(2b/D) - 2.5(d/D - 0.5)^2 - 7(2b/D)^4 \quad \text{..........(11)}
\]

\[
\text{Re} = \rho \cdot n \cdot d^5 / \mu \quad \text{..........................(12)}
\]

where, \(N_p\): power number (\(\text{~}\)), \(P\): stirring energy (W), \(a, B, p\): proportional constant (\(\text{~}\)).

The relationship between the calculated stirring energy and the apparent rate constant is shown in Fig. 15.

This relationship can be categorized into three distinct stages as well as the water model.

Stage I: Non-dispersion stage: The desulfurization rate constant, \(K\), is small, and no flux dispersion into the metal is observed.

Stage II: Transition stage: The dependency of the desulfurization rate constant, \(K\), to the power of the stirring energy is high. Flux dispersion observed.

Stage III: Complete dispersion stage: The desulfurization rate constant, \(K\), is large. Flux is completely dispersed into the hot metal, and no particle is seen on the surface.

The desulfurization rate constant, \(K\), increased remarkably at the transition of the Stage I to II. This is due to an increase of the interfacial area between flux and the hot metal by an entrainment of flux into the hot metal. The similar phenomenon were indicated in the previous studies.\(^{18,19}\)

The desulfurization rate constant, \(K\), was proportional to the 0.5th power of the stirring energy in Stage I and Stage III. It has been reported that the rate-controlling step in the desulfurization rate through the slag–metal reaction is the mass transfer rate. In those studies, \(K\) was proportional to the 0.25 to 0.54th power of the stirring energy.\(^{18-22}\) Thus, the values obtained in this work are in the range of those in the previous studies.

### 3.2.4. Estimation of Dispersed Particle Diameter

The apparent rate constant, \(K\), increased remarkably when the stirring condition changed from Stage I to III. The desulfurization rate in the complete dispersion stage, \(i.e.,\) Stage III, is 10 times larger than that in the non-dispersion stage, Stage I, as shown in Fig. 15. To evaluate the interfacial area between slag and metal, the following assumptions are made:

1. The interfacial area is equivalent to the area of the cross section of the MgO crucible, \(A_c\), in Stage I.
Aggregated desulfurization flux, whose radius is a constant, \( r_f \), completely disperses into the hot metal, and the interfacial area is equivalent to the surface area of the aggregated flux particles in Stage III.

The mass transfer rate, \( k_w \), is proportional to the 0.5th power of the stirring energy in both Stage I and Stage III.

The desulfurization rate can be expressed by Eq. (6). The apparent rate constant, \( K \), consists of the interfacial area, \( A \), the volume of the hot metal, \( V \), and the mass transfer rate, \( k_w \). The apparent rate constant, \( K \), in Stage I can be expressed as shown in Eq. (13).

\[
K_i = \frac{A_i \cdot k_w}{V} = 5 \times 10^{-4} \cdot e^{0.5} \quad \text{(13)}
\]

From Eq. (13), the interfacial area in Stage III is calculated based on the aforementioned assumptions.

\[
K_{III} = \frac{A_{III} \cdot k_w}{V} = \frac{A_{III}}{A_i} \cdot \frac{V}{V} \cdot 5 \times 10^{-4} \cdot e^{0.5} = 5 \times 10^{-3} \cdot e^{0.5} \quad \text{(14)}
\]

From Eq. (14), \( A_{III} \) can be expressed by Eq. (15).

\[
A_{III} = 10 \cdot A_i = 4\pi r_f^2 \cdot n_f \quad \text{(15)}
\]

The volume of dispersed flux can be expressed as shown in Eq. (16).

\[
\frac{4}{3} \pi \cdot r_f^3 \cdot n_f = \frac{W_f}{\rho_f} \quad \text{(16)}
\]

Where; \( r_f \): radius of aggregated flux particle, \( n_f \): number of aggregated flux particles, \( A_i \): cross-sectional area of crucible (0.045 m\(^2\)), \( W_f \): weight of flux (kg), \( \rho_f \): density of flux (kg/m\(^3\)), \( e \): stirring energy (W/ton).

From Eqs. (15) and (16), the aggregated particle diameter is 1.55 mm. In order to verify flux aggregation, slag samples were taken after a desulfurization test at 700 rpm in a 70 kg-scale induction furnace. The desulfurization slag was observed and analyzed by SEM-EDX. Average diameter of the slag was 1.4 mm. The observed diameter of the slag particles was on the same level as the calculated result.

Typical observation results by SEM and sulfur mapping by EDX are shown in Fig. 16. A sulfur-enriched area can be observed at the outer layer of the aggregated particles. From these results, it is supposed that the fine desulfurization flux (average 100 \( \mu \)m) aggregates immediately after the addition of the flux. Hence, in order to increase the interfacial area in the hot metal, it is important to avoid particle aggregation.

4. Conclusions

In order to improve the efficiency of the desulfurization process utilizing the mechanical stirring method, the effect of flux dispersion on the hot metal desulfurization reaction was investigated in 1/8-scale water model and 70 kg-scale hot metal experiments. The results of this work are summarized as follows:

(1) Flux dispersion behavior is divided into three stages, i.e., “non-dispersion,” “transition,” and “complete dispersion.” Flux dispersion behavior can be estimated from the relationship between the impeller position and the vortex depth. For achieving complete dispersion, it is important to keep the calculated vortex depth deeper than the bottom of the impeller.

(2) Desulfurization reaction behavior is also divided into three stages. The desulfurization rate increases remarkably from the “non-dispersion” to the “complete dispersion” stage, corresponding to the change in the condition of particle dispersion (increase of interfacial area). In order to achieve complete flux dispersion, and thereby secure high desulfurization efficiency, the vortex depth should reach the bottom of impeller.

(3) This relationship between the impeller position and the vortex depth is defined as the dispersion index, \( I \). When the dispersion index was over 1, complete dispersion occurred in water model experiments, and the apparent rate constant increased remarkably in hot metal experiments.

(4) The observed diameter of the desulfurization slag was 1.4 mm, which is in good agreement with the calculated value, 1.55 mm. This means that fine desulfurization flux aggregates immediately after the addition of the flux. In order to increase desulfurization efficiency, it is important to control this particle aggregation.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A )</td>
<td>Surface area (m)</td>
</tr>
<tr>
<td>( A_i )</td>
<td>Area of the cross section of the MgO crucible (m)</td>
</tr>
<tr>
<td>( a )</td>
<td>Proportional constant (–)</td>
</tr>
<tr>
<td>( B )</td>
<td>Proportional constant (–)</td>
</tr>
<tr>
<td>( b )</td>
<td>Height of impeller (m)</td>
</tr>
<tr>
<td>( D )</td>
<td>Diameter of container (m)</td>
</tr>
<tr>
<td>( d )</td>
<td>Diameter of impeller (m)</td>
</tr>
</tbody>
</table>
\( g \) : Gravitational acceleration \((=9.8 \text{ m/s}^2)\)

\( \Delta H_1 \) : Vortex depth (m)

\( \Delta H_2 \) : Vortex height (m)

\( I \) : Dispersion index (–)

\( K \) : Apparent rate constant \((1/\text{min})\)

\( k_w \) : Mass transfer rate in metal \((\text{m/min})\)

\( L \) : Impeller immersion depth (m)

\( N \) : Rotation speed (rpm)

\( N_p \) : Power number \((–)\)

\( n \) : Rotation speed \((1/\text{s})\)

\( n_f \) : Number of aggregated flux particles \((–)\)

\( n_p \) : Number of blades \((–)\)

\( P \) : Stirring energy \((\text{W})\)

\( p \) : Proportional constant \((–)\)

\( \text{Re} \) : Reynolds number \((–)\)

\( r_c \) : Radius of cylindrical rotating zone (m)

\( r_f \) : Radius of aggregated flux particle (m)

\( V \) : Volume of molten steel \((\text{m}^3)\)

\( W_f \) : Weight of flux (kg)

\( y \) : Ratio in radius of cylindrical rotating zone and container \((–)\)

\( Z \) : Liquid depth (m)

\( e \) : Stirring energy \((\text{W/ton})\)

\( \mu \) : Viscosity of liquid \((\text{Pa} \cdot \text{s})\)

\( \rho \) : Density of liquid \((\text{kg/m}^3)\)

\( \rho_f \) : Density of flux \((\text{kg/m}^3)\)

REFERENCES

3) Kagakukogakubinran, Maruzen Tokyo, (1999), 421.