1. Introduction

To establish a long-term stable operation technology with high iron productivity at a high pulverized coal rate, it is necessary to always maintain good gas and liquid permeabilities in the lower part of the blast furnace. Based on this acknowledgement, studies have been conducted on the generation, movement and accumulation of unburned char and coke fines. Studies by the authors et al. focused on the holdup composition of fines, metal and slag revealed that the fines between the raceway and the deadman contains not only coke and unburned char, but also tens of mass percent of slag fines originated from gangue minerals and ashes of pulverized coal and coke. The slag composition varies in the direction of the radius of the blast furnace because of uneven behavior of pulverized coal ash. The authors et al. presumed that the increase in the melting point and viscosity of slag caused by the radial distribution of slag composition mentioned above is a main factor that deteriorates the packing structure of the deadman.

The authors et al. took notice of technologies to improve the packing structure in the lower part of the blast furnace which was deteriorated by the abovementioned phenomenon, by blowing in flux through tuyeres. This paper deals with the desk study, laboratory experiment and test on a real blast furnace using one tuyere done for the improvement of the properties of the dripped slag held at the surface of the deadman.

2. Mechanism of Deadman Inactivation and Choice of Flux for Injection

In the injection test of serpentine through one tuyere executed as a means to improve the furnace lower filling structure, the tuyere sampler insertion depth and the deadman temperature rose greatly by the amount of the fine serpentine injection of 20 kg/t or more. It is presumed for the melting point of slag piling up in the deadman surface part to decrease by the injection of fine serpentine through tuyere, for the fine ratio (−3 mm) of the melt origin and a slag hold-up ratio to decrease greatly, and for the gas and liquid permeabilities in deadman to have been improved. In addition, the possibility that the desulfurization reaction is able to be promoted efficiently while maintaining the active state of deadman and the possibility of the low temperature operation by the serpentine injection through tuyere were suggested.

KEY WORDS: ironmaking; blast furnace; pulverized coal injection; raceway; deadman; tuyere injection; flux; serpentine; permeability; low temperature operation.
The Al₂O₃ content in the tapped slag immediately before the reaching approximately 12 to 15 mass%, which was below away from the tuyere nose (as indicated by shutdown, in the shallow part of the deadman 1.5 m or more (hereafter referred to as the slag (Fig. 1)). The CaO/SiO₂ ratio in the slag over 3 mm (hereinafter referred to as the slag (+3 mm)) was as low as approximately 0.9–1.2 in a region not more than 1 m away from the tuyere nose that corresponds to the region inside the raceway (as indicated by ◆ and ▲ in Fig. 1). The CaO/SiO₂ ratio in the slag (+3 mm) increased sharply in the inner region, reaching values of 1.4 to 1.6 between the inner part of the raceway more than 1 m away from the tuyere nose and the shallow part of the deadman (as indicated by ◆, ▼ and ▲ in Fig. 1). The Al₂O₃ content in the slag fines (−3 mm) and in the slag (+3 mm) near the tuyere nose was high (as indicated by ◆, ▼ and ◇ in Fig. 2). The Al₂O₃ content dropped toward the inside of the deadman, reaching approximately 12 to 15 mass%, which was below the Al₂O₃ content in the tapped slag immediately before the shutdown, in the shallow part of the deadman 1.5 m or more away from the tuyere nose (as indicated by ◆, ▼, ▲, ▼ and ◇ in Fig. 2). Because the CaO/SiO₂ ratio and Al₂O₃ content in the dripped slag (+3 mm) in the radial direction are substantially constant during operation with oil injection (as indicated by × in Figs. 1 and 2), it is supposed that the abovementioned radial distributions of the CaO/SiO₂ ratio and Al₂O₃ content in the slag (+3 mm) and slag fines (+3 mm) are caused by the uneven behavior of pulverized coal ash in the lower part of the blast furnace.¹⁰

Based on the above composition of the slag taken from the deadman, a hypothesis was formulated that the slag (+3 mm) and slag fines (−3 mm) with high melting point and high viscosity in the shallow part of the deadman, are one of the main causes to deteriorate the gas and liquid permeabilities in the shallow part of the deadman. To improve the gas and liquid permeabilities in the shallow part of the deadman, it is necessary to lower the melting point and viscosity of the slag (+3 mm) and slag fines (−3 mm) dripping to and held in the shallow part of the deadman. This paper discusses a technology to improve slag properties by adding flux. In choosing the flux, attention was first focused on fluxes that lower the melting point and then on their influence on viscosity.

Figure 3 is a phase diagram for the CaO–SiO₂–MgO system¹⁹ at Al₂O₃ = 15 mass%. In this diagram, ◦ and △ denote the compositions of the slag (+3 mm) and slag fines (−3 mm) in the shallow part of the deadman (at 2.3 m (between 2.15 and 2.45 m) away from the tuyere nose) taken through the No. 23 tuyere of No. 2 blast furnace at Kimitzu Works during its shutdown. It can be presumed from this phase diagram for the CaO–SiO₂–MgO–Al₂O₃ system that raising the proportion of SiO₂ in the slag will lower the melting point of the slag (+3 mm) and slag fines (−3 mm) in the shallow part of the deadman. However, raising the proportion of SiO₂ involves the possibility of increasing the viscosity of the slag (+3 mm) and slag fines (−3 mm). Therefore, the proportion of MgO, which was considered to facilitate the dripping²¹ of slag by lowering its viscosity²⁰ by acting as a network modifier in a low-FeO slag with the CaO/SiO₂ ratio of approximately 1, was also increased.

Figures 4 and 5 show changes in the melting point and viscosity resulting from adding certain proportions of SiO₂ and MgO to the slag in the shallow part of the abovementioned deadman. The melting point of the slag was estimated by substituting slag compositions (CaO, SiO₂, Al₂O₃, MgO and FeO) into the nonmetallic inclusions composition analysis model²¹ proposed by Yamada et al. and assuming the temperature at a liquid phase ratio of 100%. The viscosity of the slag was estimated by substituting the above slag compositions and the postulated slag temperature of 1500°C into the slag viscosity model proposed by Sugiyama and Nakagawa et al.²³

The melting points of the slag (+3 mm) and slag fines (−3 mm) dropped significantly with the lowering of the proportion of CaO/SiO₂. The melting points of the slags were arranged by the MgO/(MgO+SiO₂) ratio assuming the possibility of the use of the serpentine. The range of drop was great when the MgO/(MgO+SiO₂) ratio was 0.9 or above, the viscosities of the slag (+3 mm) and slag fines (−3 mm) decreased with a drop in the CaO/SiO₂ ratio, irrespective of the MgO/(MgO+SiO₂) ratio. When the CaO/SiO₂ ratio was below 1.2, changes in the viscosities of the slag (+3 mm) and slag fines (−3 mm) with a drop in the CaO/SiO₂ ratio differed with the MgO/(MgO+SiO₂).
Fig. 3. Composition of slag (+3 mm) and fine slag (−3 mm) sampled at 2.3 m from tuyere nose during shut down of Kimitsu No. 2 BF and target area to improve slag properties.

Fig. 4. Change by SiO₂ and MgO addition of melting point of slag sampled at 2.3 m from tuyere nose during shut down of Kimitsu No. 2 BF.

Fig. 5. Change by SiO₂ and MgO addition of viscosity of slag sampled at 2.3 m from tuyere nose during shut down of Kimitsu No. 2 BF.
ratio. While the viscosities increased when the MgO/(MgO + SiO₂) ratio was between 0 and 0.20 (as indicated by ◆, □ and △ in Fig. 5-1)), they remained substantially constant or decreased when the MgO/(MgO + SiO₂) ratio was between 0.30 and 0.50 (as indicated by ×, * and ♂ in Figs. 5-1) and 2). In the slags with the CaO/SiO₂ ratio under 1.2 and containing 12 to 14 mass% Al₂O₃, MgO is considered to act as a network modifier and able to lower the slag viscosity. A study of the melting point and viscosity shown in Figs. 4 and 5 revealed that the melting point is lowered without increasing the viscosity of the dripping slag when the MgO/(MgO + SiO₂) ratio is between 0.30 and 0.50. Based on this knowledge, serpentine consisting primarily of SiO₂ (approximately 40 mass%) and MgO (approximately 40 mass%) and used as a flux in the production of sintered ore was chosen (Table 1).

### Table 1. Chemical composition of serpentine (unit: mass%).

<table>
<thead>
<tr>
<th></th>
<th>T Fe</th>
<th>Fe O</th>
<th>Ca O</th>
<th>Si O₂</th>
<th>Al₂O₃</th>
<th>MgO</th>
<th>TiO₂</th>
<th>P₂O₅</th>
<th>MnO</th>
<th>S</th>
<th>C</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td>ratio</td>
<td>5.22</td>
<td>2.75</td>
<td>0.66</td>
<td>39.33</td>
<td>0.29</td>
<td>39.11</td>
<td>0.021</td>
<td>0.002</td>
<td>0.09</td>
<td>0.059</td>
<td>12.43</td>
<td></td>
</tr>
</tbody>
</table>

3. Test on Serpentine Injection through Single Tuyere on Real Blast Furnace

In a serpentine injection experiment on a hot model furnace,24) sintered ore with a reduced slag content was charged from the furnace top and a surplus serpentine powder resulting from slag reduction was blown in from a tuyere at a rate of 0.01 kg/Nm³ (approximately 15 kg/t). For comparison, an experiment to charge a mixture of lump serpentine (2 mass%) with low-slag sintered ore through the furnace top was also done. Under both experimental conditions, gas flow resistance in the lower part of the furnace dropped. Because the compositions of the raceway and tapped slags were substantially equal, it was presumed that slagging of serpentine was almost completed at the level of the raceway. Because, in addition, the compositions of the raceway slags under both conditions were substantially equal, it was presumed that slagging of serpentine blown in through the tuyeres was almost completed at a depth of 1.5 mm or larger accounted for 57 and 21 mass%. Serpentine was blown in at three different rates, of 6.3, 20.4 and 30.0 kg/t. Serpentine injection was done for a little less than three days before the shutdown, except in the case of 6.3 kg/t.

Before the shutdown the serpentine injection was stopped about the same time with the pulverized coal injection just before decreasing of the blast volume for the shutdown. During the shutdown immediately after the injection test, a drop-in sampler having an inside diameter of 80 mm was inserted through the No. 23 tuyere. In the drop-in sampler the lid is done in the slide and upper filling materials are gathered by the vibration. The depth of the sampler inserted was determined and the furnace burden was sampled. The sampled burden was sifted through a 3 mm mesh sieve and the oversize which was larger than 3 mm after removing lump coke was defined as the fines.25) The metal holdup, slag holdup, and fines (<3 mm) were subjected to chemical analysis. The metal holdup was analyzed for seven elements (C, Si, Mn, S, P, Ca and Al). The slag holdup and fines (<3 mm) were analyzed for ten constituents (CaO, SiO₂, MgO, Al₂O₃, MnO, P₂O₅, S, T.C, T.Fe and FeO). The values determined by chemical analysis of the slag holdup were corrected for metal carbon and ash in coke. The values determined by chemical analysis of the metal holdup were corrected for slag content. Based on the analysis results of the metal and slag holdups, the distribution ratio between metal and slag ([%S]/[%S]) was determined. The fines (<3 mm) was classified into that from coke and that from the melt. The lump coke between 15 and 25 mm in size was pulverized and decalcified. The fines thus treated was subjected to an X-ray analysis to determine the degree of graphitization on the basis of which the hysteresis temperature of lump coke was estimated.

### Table 2. Size distribution of serpentine used in one tuyere injection test of Kimitsu No. 2 BF.

<table>
<thead>
<tr>
<th>Size (mm)</th>
<th>Weight ratio (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;+3</td>
<td>0.21</td>
</tr>
<tr>
<td>1~0.5</td>
<td>0.25</td>
</tr>
<tr>
<td>0.5~0.25</td>
<td>0.18</td>
</tr>
<tr>
<td>0.25~0.125</td>
<td>0.14</td>
</tr>
<tr>
<td>0.125~0.063</td>
<td>0.15</td>
</tr>
<tr>
<td>0.063~0.045</td>
<td>0.05</td>
</tr>
<tr>
<td>&lt;0.045</td>
<td>0.02</td>
</tr>
</tbody>
</table>

### Table 3. Outline of one tuyere serpentine injection test of Kimitsu No. 2 BF.

<table>
<thead>
<tr>
<th>Period</th>
<th>Serpentine injection rate (kg/t)</th>
<th>Injection time (h)</th>
<th>7 days average POR before shut down (kg/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>00 Apr 20~21</td>
<td>6.3</td>
<td>12.4</td>
<td>119</td>
</tr>
<tr>
<td>00 May 22~25</td>
<td>20.4</td>
<td>62.6</td>
<td>117</td>
</tr>
<tr>
<td>00 Nov 11~13</td>
<td>30.0</td>
<td>62.0</td>
<td>106</td>
</tr>
</tbody>
</table>
3.2. Test Results

3.2.1. Deadman Packing Structure

Figure 6 shows the relationship among the pulverized coal rate, volume of serpentine injection, and the depth of sampler insertion through a tuyere which is decided depending on the thrust (6t) of the sampler. While the depth of sampler insertion increased as the pulverized coal rate lowered, it increased greatly when serpentine was blown in. The increase in the depth of sampler insertion was eminent when 20 kg/t/tuyere or more serpentine was blown in. When the injection of serpentine was at 30 kg/t/tuyere, the fines ratio (≤3 mm) in the shallow part of the deadman (1.5 m or more away from the tuyere nose) dropped greatly (Fig. 7) and the holdup ratio in the slag (≥3 mm) also dropped (Fig. 8). The hysteresis temperature of coke in the deadman at 1.5 m or more away from the tuyere nose rose sharply from 1500°C to 1700°C (Fig. 9). It is presumed that the abovementioned improvement of the packing structure in the deadman caused a substantial increase in the depth of sampler insertion through the tuyere.

3.2.2. Reduction and Temperature Level in the Deadman

Figures 10 and 11 show the radial distributions of the FeO content and the MnO/Mn ratio in the slag sample taken through the tuyere during the shutdown after the serpentine injection test at an injection rate of 30 kg/t/tuyere (continued for 62 h). The serpentine injection significantly lowered the FeO content in the slag and MnO/Mn ratio in the deadman.
man at 1.5 m or more away from the tuyere nose. While the FeO content after the serpentine injection test was the same as that in the slag tapped immediately before the shutdown, the MnO/Mn ratio was lower than that during tapping immediately before the shutdown. It is presumed that such a good reduction and a high temperature level maintained in the deadman resulted from the improvement of the gas and liquid permeabilities in it brought about by the injection of serpentine.

Also, the (%S)/[%S] after the serpentine injection increased greatly over the same compound basicity \((\text{CaO}/\text{MgO})/(\text{SiO}_2/\text{Al}_2\text{O}_3)\) (Fig. 12). This shows that the improvement in the packing structure of the deadman has a great influence on the (%S)/[%S].

### 3.3. Discussion

#### 3.3.1. Relationship between the Composition and Properties of Dripping Slag and the Deadman Packing Structure Improving Mechanism

**Figures** 13 and 14 show the radial distributions of the CaO/SiO\(_2\) ratio in the slag (+3 mm) and slag fines (−3 mm) in the sample taken through the No. 23 tuyere during the shutdowns before and after the serpentine injection test at a rate of 30 kg/t/tuyere (continued for 62 h). Serpentine injection greatly lowered the CaO/SiO\(_2\) ratio in the slag (+3 mm) and slag fines (−3 mm) in the range of 0.3 and 0.6. This tendency is particularly eminent between the inner part of the raceway and the shallow part of the deadman between 1 m and 3 m away from the tuyere nose. As a consequence, the estimated melting points of the slag (+3 mm) and slag fines (−3 mm) after serpentine injection dropped (Figs. 15 and 16). The estimated viscosity at the temperatures (1 800°C between 0 m and 1 m away from the tuyere nose, 1 550°C between 1 m and 2 m away, and 1 500°C over 2 m away) based on the hysteresis temperature of the lump coke before serpentine injection (as indicated by ◆ in Fig. 9) was substantially similar with the estimated viscosity before serpentine injection (as indicated by ◆ and □ in Figs. 17 and 18). However, the estimated viscosity under the temperature conditions (1 800°C between 0 m and 1 m away...
from the tuyere nose, 1 700°C between 1 m and 2 m away, and 1 700°C over 2 m away) based on the hysteresis temperature of the lump coke after serpentine injection (as indicated by $H_17039$ in Fig. 9) dropped greatly (as indicated by $H_11012$ in Figs. 17 and 18).

As explained in 3.2.1, the ratio of the fines ($H_11002$) in the shallow part of the deadman at 1.5 m or more away from the tuyere nose dropped greatly when the sampler insertion depth through the tuyere increased during the shut down after the serpentine injection test at a rate of 30 kg/t (continued for 62 h). This fines ratio drop resulted from the lowering of the ratios of the fines ($H_11002$) from coke (Fig. 19) and the fines ($H_11002$) from the melt (slag and metal) (Fig. 20). It is supposed that the drop of the ratio of the fines ($H_11002$) from the melt resulted from the acceleration of the melting and dripping of the slag and metal fines ($H_11002$). This, in turn, is as a result because of an increase in the deadman temperature (Fig. 9) and a drop of the viscosity of the slag fines ($H_11002$), through the improvement of the gas permeability in the shallow part of the deadman (Fig. 21).

The decrease in the slag holdup (+3 mm) is a composite effect of the following changes. One change was an increase in the deadman temperature (Fig 9) which resulted from the improvement of the gas and liquid permeabilities in the shallow part of the deadman, that was brought about by the lowering of the melting point and viscosity of the slag fines ($H_11002$) (Figs. 15 and 17) by serpentine injection. The other was due to the direct lowering (Figs. 16 and 18) of the melting point and viscosity of the slag (+3 mm) by serpentine injection (Fig. 21).

The technology to blow in serpentine that lowers the
melting point of the slag dripping into or held in the outer periphery of the raceway and the deadman is considered to become a seed of technologies to operate blast furnaces at low temperatures of pig iron and slag.

3.3.2. Change in Slag Composition in the Deadman before and after Serpentine Injection and Its Mechanism

Figure 22 shows the actual compositions of the slag (+3 mm) and slag fines (−3 mm) accumulated in the shallow part of the deadman before and after serpentine injection. The changes in the actual MgO contents in the slag (+3 mm) and slag fines (−3 mm) caused by serpentine injection were smaller than those in the estimated MgO contents indicated by the arrow in Fig. 22. The authors studied if abovementioned phenomenon can be explained by the difference between the compositions of the dripping and residual slags.

According to the dripping test of the FeO–CaO–SiO₂–Al₂O₃–MgO type slag conducted by Kumano and Hino, the MgO content in the dripping slag was higher than that in the residual slag when the slag contained approximately 2 mass% MgO, not more than 30 mass% FeO, and with the CaO/SiO₂ ratio at 0.6 to 0.8. When the MgO content was between 5 and 10 mass%, however, the MgO content in the residual slag was higher than that in the dripping slag. An inference from above knowledge shows that the possibility that the MgO content in the dripping slag is higher than that in the residual slag with the slag in the lower part of the blast furnace (that contains 5 to 10 mass% MgO and not more than 20 wt% FeO, with the CaO/SiO₂ ratio at 1.0 to 1.3) is small.

Figure 23 shows the radial distribution of the MgO/Al₂O₃ ratio in the slag sampled through the tuyere during shutdown. The MgO/Al₂O₃ ratio was small in the region not more than 1 m away from the tuyere nose and substantially similar with the value on tapping in the deeper region. While this phenomenon may be ascribable to the high content of ash from coke and pulverized coal near the tuyeres, reduction and vaporization of MgO in the slag also may possibly be responsible as shown by Eq. (1) because the MgO/Al₂O₃ ratio is sometimes extremely small.

\[
\Delta G^\circ = -969,957 + 29,833 \log T \quad [\text{J/mol}]^{26,27}
\]

Figure 24 shows the partial pressure of Mg in the above-mentioned reaction calculated by assuming that the partial pressure of CO in the high-temperature region at the tuyere nose. Here, the activity coefficient of MgO in the slag
(γ_{MgO}) was derived from the following equation based on the report by Kume et al.\textsuperscript{28)}

\[
\gamma_{MgO} = 1.542 \cdot (\%CaO) + 1.544 \cdot (\%SiO_2) \\
+ 1.583 \cdot (\%Al_2O_3) + 1.352 \cdot (\%MgO) \\
- 151.96 \text{ (at 1 600°C)} \tag{2}
\]

Here, the temperature dependence of MgO considered on the basis of a regular solution approximation was used in the calculation. The partial pressure of MgO calculated based on the composition shown in Table 4 was approximately 10^{-3.2} to 10^{-2.9} atm. This leads to an inference that the partial pressure of MgO becomes high in highly reduced slags.

By using the above values, the possibility of the desulfurization of sulfur in molten iron by Mg gas shown in Eq.(3) in the high-temperature region at the tuyere nose was studied.

\[
\text{Mg (g)} + \text{S(g)} = \text{MgS (s)} \tag{3}
\]

\[
\Delta G_0^\circ(3) = -437020 + 185.477T \text{ [J/mol]} \tag{26,29}
\]

\[
\Delta G_\gamma(3) = \Delta G_0^\circ(3) + RT \ln K_\gamma(3) \\
= \Delta G_\gamma(3) + RT(\ln \gamma_{MgS} + \ln X_{MgS} - \ln P_{Mg} - \ln a_s) \tag{5}
\]

Here, the activity coefficient of MgS in the slag (\(\gamma_{MgS}\)) was evaluated by the following method.

\[
\text{MgO (s)} + 1/2 \text{S}_2 (g) = \text{MgS (s)} + 1/2 \text{O}_2 (g) \tag{4}
\]

\[
K_\gamma(3) = (a_{MgS} P_{O_2}^{1/2}) (a_{MgO} P_{S_2}^{1/2}) \tag{5}
\]

Here, the following relation can be derived from the definition of the sulfide capacity (C_\text{S}) that indicates the desulfurizing capacity of the slag.

\[
(P_0/P_S)^{1/2} = C_\text{S}(\%S) \tag{6}
\]

Equation (7) was obtained by substituting Eq. (6) in Eq. (5) and rearranging.

\[
a_{MgS} = a_{MgO}(\%S) K_\gamma/C_\text{S} \\
\gamma_{MgS} = a_{MgO}(\%S) K_\gamma(1/C_\text{S} \cdot X_{MgS}) \tag{7}
\]

\[
\gamma_{MgS} \text{ for any given slag composition can be derived from Eq. (7). The following equation was used for } C_\text{S}\text{.} \tag{30)}
\]

\[
\log C_\text{S} = 12.6 \cdot A - 12.3 \tag{8}
\]

The sulfur content in the molten iron sampled through the tuyeres of blast furnaces in operation was approximately 0.1 mass%, \(f_S\) was approximately equal to 3, and the result shown in Fig. 25 was obtained by assuming that \(a_s = 0.3\) (based on 1 mass%). Because \(\Delta G_\gamma(3) < 0\) in the high-temperature region, it is inferable that desulfurization according to Eq. (3) can occur.

The result of the above thermodynamic study leads to an inference that it is possible that the MgO in the high-temperature region in and near the raceway reacts with the C in coke. It is further inferable that the Mg gasified by the abovementioned reaction reacts with the S in the metal dripping into and near the raceway to form MgS,\textsuperscript{32)} that is then absorbed by the slag dripping from the raceway to the shallow part of the deadman and discharged through the taphole.

5. Conclusion

A desk study, laboratory experiment and test on a real blast furnace using one tuyere were conducted for the improvement of the properties of the dripped slag held at the surface of the deadman, with attention focused on the technology to improve the packing structure in the lower part of the blast furnace by blowing in flux through tuyeres. The following points can be made:

1. The melting point and viscosity of the dripping slag were calculated by varying the proportions of SiO\textsubscript{2} and MgO. Fluxes having the MgO/(MgO/SiO\textsubscript{2}) ratio between 0.30 and 0.50 proved favorable for lowering the melting point of the dripping slag without increasing its viscosity. From the practical viewpoint, serpentine consisting primarily of SiO\textsubscript{2} and MgO was chosen as the flux for injection
through tuyeres.

(2) In the test to blow in serpentine through a single tuyere, the depth of the sampler inserted through the tuyere increased greatly when serpentine was blown in at a rate of 20 kg/t or more. When the insertion depth of the sampler increased, the proportion of the fines (−3 mm) and the holdup ratio of the slag (+3 mm) in the shallow part of the deadman dropped and the hysteresis temperature of the coke in the deadman at 1.5 m away from the tuyere nose rose greatly.

(3) It was inferred that the improvement of the packing structure of the deadman described above resulted from the improvement of the gas and liquid permeabilities in the deadman. This was achieved through the substantial lowering of the proportion of the fines (−3 mm) and the holdup ratio of the slag (+3 mm) from the melt. This itself occurred as a result of the lowering of the CaO/SiO₂ ratio and melting point of the slag (H₁₁₀₀₁) increased, the proportion of the fines (−3 mm) and slag fines (−3 mm) in the shallow part of the deadman, which in turn was caused by the injection of serpentine.

(4) It was suggested that direct injection of serpentine to the raceway has possibilities for the efficient acceleration of desulfurization while maintaining the active state of the deadman and the realization of blast furnace operation at low temperatures.

Nomenclature

\( a_i \): Activity of component \( i \)

\( \gamma_i \): Activity coefficient of component \( i \)

\( X_i \): Mole fraction of component \( i \)

\( \Delta G_{\text{f}(\text{in})} \): Standard free energy change in reaction of Eq. (n) [J/mol]

\( \Delta G_{\text{f}(\text{in})} \): Free energy change in reaction of Eq. (n) [J/mol]

\( K_p \): Equilibrium constant in reaction of Eq. (n)

\( P_c \): Partial pressure of component \( i \) (atm)

\( C_s \): Sulfide capacity

\( \%S \): Sulfur concentration in slag [mass%]

\( \Lambda \): Optical basicity

\( T \): Temperature [K]

\( R \): Gas constant [J/(mol·K)]

\( f_S \): Activity coefficient of S in molten iron

REFERENCES


