Effect of High Al_2O_3 Slag on the Blast Furnace Operations

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Increasing the Al_2O_3 content in the blast furnace slag, the blast furnace operations tend to make troubles such as excess accumulation of molten slag in the blast furnace hearth and increasing pressure drop at the lower part of the blast furnace. So, it will be important to keep good slag fluidity at the blast furnace operations such as, drainage of tapping and keeping good permeability.

In order to clarify the effect of high Al_2O_3 slag fluidity on the blast furnace, high Al_2O_3 slag (20%) test operations of experimental blast furnace have been carried out. Investigation results of the test operation are as follows;

1) Slag MgO improves the hearth drainage rate at high Al_2O_3 slag operation.
2) Permeability of the dripping zone is improved by decreasing slag CaO/SiO_2, at high Al_2O_3 slag operation of the blast furnace.
3) It was verified that the slag drainage phenomena were able to described by the fluid model.
4) The optimum composition of high Al_2O_3 slag of the blast furnace is high MgO and low CaO/SiO_2.

KEY WORDS: experimental blast furnace; Al_2O_3; slag; viscosity; drainage; dripping; permeability.

1. Introduction

The slag fluidity in a blast furnace affects softening-melting behavior in a cohesive zone, permeability in the lower part of a furnace due to liquid hold-up in a dripping zone, liquid flow in a furnace hearth, and the ability of the drainage slag by a taphole.

The slag fluidity is affected by temperature and composition, with the latter influenced by ore gangue minerals and ash materials of coke and pulverised coal. CaO/SiO_2 in the slag, even in slag compositions, is adjusted in Japan to a range of 1.2 to 1.3 in concentration by an auxiliary material in terms of fluidity and desulfurization ability.

The Al_2O_3 concentration in the slag is considered to be a factor that degrades the slag fluidity, which is semi-empirically set in Japan at the upper limit of about 15% to 16% in order to avoid the accumulation of the iron slag and the deterioration of permeability in the lower part of the furnace.

Meanwhile, in recent blast furnace operations, slag-reduction is promoted from a viewpoint of SiO_2-reduction in a sintered ore, facilitating improvement of permeability in the blast furnace, a reduction in slag volume, and environmental-response. However, as slag volume decreases, the concentration of Al_2O_3 in the slag increases relatively, even if the Al_2O_3 in the ore is not changed. Moreover, from the viewpoint of the supply and demand of raw materials and fuels that have recently become in tight supply, the increase in concentration of Al_2O_3 is inevitable. The issue now is to present clear guidelines with regards to the upper limit of Al_2O_3 concentration in the slag.

In formulating the guidelines, it is important to understand the behavior of slag in the blast furnace. Various kinds of studies of the behavior have been undertaken. On the matter of slag fluidity in the blast furnace, there are studies1–4) on the estimation of viscosity as liquid physical properties, quantitative evaluations5) of molten pig iron and slag tapping phenomena in the furnace hearth by experiments with models and by numerical analysis, and evaluations6–13) of effects on the pressure drops in liquid flow in the dripping zone. It is also pointed out that the increase of ore-Al_2O_3 affects not only the strength of a sintered ore,12) but also its characteristics13–15) at high-temperatures in the cohesive zone.

For evaluation in an actual blast furnace, a test16) to increase (20%) Al_2O_3 in the slag for about one month was carried out at Muroran1BF in 1968. Only the relationship between desulfurization performance and viscosity in the slag was considered, but there was no reference with respect to the upper limit of Al_2O_3 concentration in the slag in the blast furnace.

The examination described above was limited to a single phenomenon. The in-furnace phenomena were not systematically analyzed. Thus, for the effects of slag fluidity, focusing Al_2O_3 on each area in the blast furnace, we focus on permeability in the lower part of the blast furnace and slag drainage in the furnace hearth, and conduct a high Al_2O_3 slag operation test17,18) with an experimental blast furnace19) in order to systematically evaluate permeability and drainage.

Based on the results, the effects of the viscosity and crystallization temperature governing slag fluidity on the permeability in the lower part of the blast furnace and slag drainage were evaluated for each area.

For slag drainage, the iron slag remaining in the actual blast furnace was considered from the evaluation of fluidity from the experimental results by numerical analysis. For permeability in the lower part of the blast furnace, an evaluation of results from the experimental blast furnace was conducted together with a dripping experiment for a coke-bed layer of the cohesive slag and the softening-melting test results of high Al_2O_3 sinters, and thought was given to the dripping zone and the cohesive zone. In addition, the slag design was considered, including CaO/SiO_2 and MgO from the comprehensive blast furnace...
evaluations of the high Al₂O₃ slag operation.

2. Test Condition

Before carrying out the operation test for the high Al₂O₃ slag in the experimental blast furnace, based on the view point of the preceding section, the concept for setting test conditions and the operation conditions, including facility conditions, was described.

2.1. Slag Design

In order to specify the slag viscosity and the slag-crystallization temperature as indexes for evaluation of slag fluidity as operational factors, slag design was conducted for each respectively and independently, changing them based on the equation estimated by Hoshi et al.3)

According to the estimated equation, the viscosity changes little and the crystallization temperature increases linearly as CaO/SiO₂ increases around CaO/SiO₂ range of 1.1 to 1.5. Thus, in the range, a decrease of CaO/SiO₂ and an increase of MgO make changes independent of viscosity and crystallization temperature possible under the condition of the high Al₂O₃ slag. For these reasons, the high Al₂O₃ in the sintered ore with CaO/SiO₂ and MgO adjusted was manufactured to provide the test.

2.2. Used Materials

Table 1 indicates each composition of high Al₂O₃ sinter, ore, auxiliary material, coke, and pulverized coal that were used for the test operation.

The oil coke with no ash content, having a high caloric value, was used at the rate of 50% of all coke to decrease the reduced agent rate (RAR) and the amount of slag to be used in the experimental blast furnace.

Two kinds of sinters with high Al₂O₃ content were produced, of which sinter A contained high MgO and sinter B contained high MgO and low CaO/SiO₂.

The auxiliary materials used for the slag design were silica stone, serpentine stone, dolomite, and limestone. The particle size of the sintered ore used was 10–25 mm, and that of the coke was 15–30 mm.

2.3. Experimental Blast Furnace (EBF) Conditions

The experimental blast furnace (EBF)14) shown in Fig. 1. The internal volume of 3 m³ and a hearth diameter of 0.9 m. It has three tuyeres arranged at intervals of 120 degrees in a circumferential direction, and one taphole located at the lowest part of the bottom of the blast furnace.

Each of the dedicated hoppers for the coke and ore were placed at the top of the furnace and the stock levels were fixed at a height of 4.5 m from tuyere level. From each hopper, it is discharged in order, and layered is charged with coke and ore.

At that time, the uniformity of the thickness of the layer over the entire surface of the furnace top was checked by the actual measurement. Static pressure gauges were placed at pitches of 150 to 300 mm in the direction of height and a sonde for sampling the furnace during operation, from cohesive zone and dripind zone were provided. A stock level gauge, and a molten pig iron and slag level gauge, were also provided, too. After blow-in, stable conditions in EBF operation were checked and then the furnace operation was shifted to the experimental case. After a melting operation of about 2 h under a predetermined blasting condition, the molten pig iron slag of about 1 ton that had been accumulated in the furnace was discharged completely under reduced pressure by tapping the molten pig iron. After the tapping, the reduced pressure was returned to the predetermined blasting pressure. The continuous operation was carried out by repeating the cycle (1 TAP). The slag amount for each TAP was fixed at 225 kg, as shown in Table 2 for permeability evaluation. The blasting condition for pulverized coal of 200 kg/pt was made equivalent in all cases (equivalent in oxygen excess coefficient).

2.4. Practice Case

The practice case settings are shown in Table 3. The MgO and CaO/SiO₂ slag were changed by the two types of sintered ores under the high Al₂O₃. In CASE 1 (base) the slag Al₂O₃ content was established at 13 to 14% and, in other cases, the content was increased to 17 to 21%. In CASE 2 a high crystallization temperature was set because of the increase of MgO, and in CASE 3 a high viscosity condition was set because of the lower CaO/SiO₂. In CASE 4, the condition was a high Al₂O₃ without adjusting auxiliary raw materials in order to permit a comparison of the cases, and in CASE 5 the viscosity and crystallization were lowered to the base values because of the increase in MgO and the lower CaO/SiO₂. The base value of...
CaO/SiO₂ was set at 1.45. This is higher than that in the actual blast furnace, because a lower width was ensured in the previous change range and the increase in slag amount was suppressed during the operation with a high reduction material ratio.

3. Test Results

The test operation was carried out for 4 days (all of 35 taps), as shown in Table 4. Measurement values of the viscosity and crystallization temperature shown in Fig. 2, Table 4 were obtained by continuously measuring vibration pieces during the cooling (2°C/min), after pulverizing slag for each case; and reheating test pieces to 1550°C that had been prepared by preliminarily melting. The measurement values were within the estimation range (viscosity of 2 poise, crystallization temperature of 20°C) when the estimation equation was introduced. As a result, the values satisfied the setting conditions in Table 3.

The condition in which the difference in viscosity is 6 poise or greater, and the difference in crystallization temperature is about 100°C or greater, were set between CASEs in the test. Thus, the condition makes superior effect evaluation possible at the above estimation accuracy.

Table 4. The results of experimental blast furnace operation.

<table>
<thead>
<tr>
<th>CASE</th>
<th>CASE2</th>
<th>CASE3</th>
<th>CASE4</th>
<th>CASE5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pig output (kg/tap)</td>
<td>784</td>
<td>695</td>
<td>734</td>
<td>873</td>
</tr>
<tr>
<td>Slag output (kg/tap)</td>
<td>225</td>
<td>225</td>
<td>225</td>
<td>225</td>
</tr>
<tr>
<td>Molting time (min)</td>
<td>99.7</td>
<td>96.6</td>
<td>96.8</td>
<td>108.5</td>
</tr>
<tr>
<td>RAR (kg/t)</td>
<td>742</td>
<td>783</td>
<td>823</td>
<td>773</td>
</tr>
<tr>
<td>Top gas temp (°C)</td>
<td>360</td>
<td>347</td>
<td>406</td>
<td>410</td>
</tr>
<tr>
<td>Top gas Al₂O₃ (%)</td>
<td>40.5</td>
<td>40.5</td>
<td>37.1</td>
<td>40.5</td>
</tr>
<tr>
<td>Pig temperature (°C)</td>
<td>1457</td>
<td>1446</td>
<td>1428</td>
<td>1418</td>
</tr>
<tr>
<td>[C] (%)</td>
<td>4.75</td>
<td>4.73</td>
<td>4.56</td>
<td>4.48</td>
</tr>
<tr>
<td>[Si] (%)</td>
<td>0.77</td>
<td>0.73</td>
<td>0.7</td>
<td>- 0.63</td>
</tr>
<tr>
<td>[S] (%)</td>
<td>0.025</td>
<td>0.025</td>
<td>0.055</td>
<td>0.055</td>
</tr>
<tr>
<td>Slag temperature (°C)</td>
<td>1533</td>
<td>1541</td>
<td>1563</td>
<td>1500</td>
</tr>
<tr>
<td>(Al₂O₃) (%)</td>
<td>13.4</td>
<td>18.6</td>
<td>20.4</td>
<td>19.2</td>
</tr>
<tr>
<td>(MgO) (%)</td>
<td>5.36</td>
<td>8.5</td>
<td>4.75</td>
<td>4.83</td>
</tr>
<tr>
<td>f(CaO) (%)</td>
<td>1.49</td>
<td>1.46</td>
<td>1.21</td>
<td>1.14</td>
</tr>
<tr>
<td>Viscosity poise</td>
<td>2.35</td>
<td>2.5</td>
<td>5.95</td>
<td>6.03</td>
</tr>
<tr>
<td>Viscosity 1500°C poise</td>
<td>3.07</td>
<td>3.51</td>
<td>6.04</td>
<td>5.64</td>
</tr>
<tr>
<td>Crystallization temperature (°C)</td>
<td>1334</td>
<td>1430</td>
<td>1376</td>
<td>1404</td>
</tr>
<tr>
<td>ΔT°C</td>
<td>179</td>
<td>111</td>
<td>127</td>
<td>96</td>
</tr>
</tbody>
</table>

Table 3. The test case condition of experimental blast furnace.

<table>
<thead>
<tr>
<th>CASE</th>
<th>CASE2</th>
<th>CASE3</th>
<th>CASE4</th>
<th>CASE5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slag viscosity (poeise)</td>
<td>High</td>
<td>Base</td>
<td>High</td>
<td>Base</td>
</tr>
<tr>
<td>Slag crystallization temperature (°C)</td>
<td>(1365-1355)</td>
<td>(1365-1355)</td>
<td>(1365-1355)</td>
<td>(1365-1355)</td>
</tr>
<tr>
<td>Slag Al₂O₃ (%)</td>
<td>Base</td>
<td>High</td>
<td>Base</td>
<td>High</td>
</tr>
<tr>
<td>Slag MgO (%)</td>
<td>Base</td>
<td>(4.5-5.5)</td>
<td>Base</td>
<td>(4.5-5.5)</td>
</tr>
<tr>
<td>Slag CaO/SiO₂ (×)</td>
<td>Base</td>
<td>Low</td>
<td>Base</td>
<td>Low</td>
</tr>
<tr>
<td>Lime/alkali Silicate Rock</td>
<td>Dolomite Serpentine</td>
<td>Silicate (non) Serpentinite</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The description appears in Table 4 KR14 showing the index of permeable resistance and the slag discharge (slag drainage) rate in each case. In CASE 2, the slag Al₂O₃ and crystallization temperature are, in comparison to CASE 1, higher than those of CASE 1; and the slag drainage rate does not decrease, but the KR index increases.

In CASE 3, the slag Al₂O₃ and viscosity are high; and the slag drainage rate decreases and the KR index increases. CASE 4 is similar to CASE 3; the high Al₂O₃ is the same as CASE 1, but the viscosity of CASE 4 is lower than that of CASE 1. In CASE 5 with crystallization temperature unchanged, the slag drainage rate increases and the ventilation resistance decreases.

4. Consideration

4.1. Evaluation of Slag Drainage

4.1.1. Method for Evaluating Slag Drainage Speed

The taphole placed at the lowest part of the blast furnace bottom of EBF is opened by a hole-opening machine. The molten pig iron is discharged and subsequently the molten slag is discharged. Thus, a pig-slag drainage rate can be measured independently.

Figure 3 shows weighing capacity by the load cell placed at the molten iron ladle and a pig-iron temperature (the emersion temperature measurement and an irradiation temperature thermometer) while tapping slag. The comparative case is provided for the relationship between the high viscosity condition (CASE 3) indicated by a solid mark and a solid line and the reference condition (CASE 1) indicated by dashes and an open mark.

The pig-slag drainage rate expresses variation in rate of time of a load (gradient in Fig. 3), and the gradient change at a load of 650 kg or greater shows the change in density of the pig-slag.

Because of the increase in the temperature at the same time, the change in timing from the molten iron discharge to the slag discharge since the beginning of the hole-opening was detected.

In this study, the slag drainage rate was quantified as the index of slag drainage. However, since the measurement
values for the slag drainage rate are affected by the taphole condition in each TAP; especially the taphole diameter by the operation condition and hole-opening work, it was necessary to convert actual measurement values to those of the same taphole condition in order to evaluate the effect of the viscosity on the slag drainage rate.

After estimating a taphole diameter in each case from the molten iron discharge rate with little change in viscosity, the slag discharge rate was calculated for the same taphole diameter.

\[
A_{t} \mu_{t} = A_{t} \mu_{t}, \quad \text{......................................(1)}
\]

\[
\frac{u_{t}^{2}}{2} + g z_{t} + \frac{P_{t}}{\rho} = \frac{u_{t}^{2}}{2} + g z_{t} + \frac{P_{t}}{\rho} + F_{\text{loss}} \quad \text{......................................(2)}
\]

\[
F_{\text{loss}} = \frac{(\Delta P_{b} + \Delta P_{f})}{\rho} \quad \text{......................................(3)}
\]

\[
\left( \frac{\Delta P_{b}}{L_{b}} \right)_\text{Cokebed} = 150 \left( \frac{1 - \varepsilon_{b} \rho_{hi}^{2}}{e_{b}^{3} d_{p}^{3}} \right) + 1.75 \left( \frac{1 - \varepsilon_{b} \rho_{hi}^{2}}{e_{b}^{3} d_{p}^{3}} \right) \quad \text{........................................(4)}
\]

\[
(\Delta P_{f})_{\text{taphole}} = 4 f \left( \frac{u_{t}^{2}}{2} \right) \frac{L_{t}}{D_{th}} \rho \quad \text{......................................(5)}
\]

\[
f = \frac{16}{Re} \quad (Re > 2000) \quad \text{......................................(6)}
\]

\[
\frac{1}{\sqrt{f}} = 2.28 - 4 \log_{10} \left( \frac{e}{D_{th}} \right) \quad (Re > 10000) \quad \text{..................................(7)}
\]

\[
Re = \frac{\rho u_{th} D_{th}}{\eta} \quad \text{......................................(8)}
\]

Assuming a natural outflow, considering the molten pig iron in the hearth of EBF, a pouring hearth part to describe molten slag discharge behavior, and a pressure drop in the taphole tube, a material balance Eq. (1) and Bernoulli’s equation, Eq. (2) are prepared in an isothermal system. Subscripts 1 and 2 of Eqs. (1) and (2), respectively, indicate the pouring hearth part and the inside of the taphole part.

Equation (3) is the pressure drop formula, which consists of the pouring hearth part in Eq. (4) and the taphole part in Eq. (5).

Here, before calculating Eq. (4), the coke-free layer level in the operation was estimated.

In the continuous measurement of the stock level during the molten iron tapping, the discharged pig slag volume is nearly equal to the amount of the molten pig iron present in the coke-free layer, as shown in Fig. 4.

At that time, the estimated level of liquid was equal to the value indicated by the liquid level gauge immediately before the molten pig hole tapping.

Accordingly, the assumption that molten pig iron is present only in the coke-free layer and that slag is present in the coke-bed layer could be made, and thus the Eq. (4) reflects only the coke-bed layer part.

First, an actual taphole diameter in each TAP was calculated from the measurement value of the discharge rate of the molten pig iron with little change in viscosity in compared to molten slag.

Actual taphole diameters calculated for all measurement values 33TAP are shown in Table 5.

Although the drill diameter of the hole-opening machine is 40 mm, the values resulting from the calculation are distributed in the range of 35 to 60 mm. Next, for the molten slag, the actual slag drainage rate measured for each TAP was converted to the reference taphole diameter (= 40φmm) by Eqs. (1) to (8), based on the relationship between viscosity at the taphole diameter and the calculated slag drainage rate obtained above.

Figure 5 indicates the slag drainage rate before and after the conversion.

The method has improved the correlativity between actual slag drainage rate and calculated slag drainage rate.

4.1.2. Effects of Viscosity and Crystallization Temperature on Slag Drainage

Figure 6 shows the effects of the slag viscosity and the slag crystallization estimated from the actual slag chemical analysis values on the slag drainage rate.

With an increase in slag viscosity, the slag drainage rate decreases, the gradient which is equal to the calculated value. As a result of stratification of data in the difference between the crystallization temperature and the slag temperature, it was not found that the slag crystallization temperature provided a greater influence than others on slag drainage. Figure 7 shows only the influence of the slag composition by excluding the influence of temperature on the slag drainage rate and, then, by correcting temperature to that in the 1 500°C reference.

According to Table 4, with an increase of Al, OI slag, such as CASE 1 to CASE 4 and 3 or CASE 5 to CASE 2, the slag drainage rate decreases due to the increase in the viscosity. However, with the MgO increase, the viscosity is lowered and the slag drainage rate increases. By use of the above, the estimation equation used in the report is proved to be proper and, also, it is shown that the viscosity can be controlled by changes in the slag composition.

4.1.3. Influence by the Slag Fluidity on the Actual Blast Furnace

It becomes clear that slag drainage behavior is a fluidization phenomenon due to viscosity, and, thus, an evaluation of the actual blast furnace is carried out as follows. In the case of EBF, the taphole is arranged in the bottom part, and the molten pig iron and the slag, respectively, are discharged and, thus, one-dimensional handling is possible in Eqs. (1) through (8). However, in the case of an actual blast furnace, the taphole is located near the interface between the slag and the metal. Thus, changes in the interface between the slag and the metal should be considered.

Accordingly, the fluidity analysis was carried out in a three-dimensional isothermal system consisting of a slag phase, a metal phase, and a gas phase. Equation (9) is the equation of continuity; Eq. (10) is the Navier–Stokes equation, and Eq. (11) expresses the interaction of the fluid and the coke-bed layer.

\[
\frac{\partial}{\partial t} \varepsilon + \frac{\partial}{\partial x_{j}} (\varepsilon u_{j}) = 0 \quad \text{........................................................(9)}
\]

\[
\frac{\partial}{\partial t} (\varepsilon u_{j}) + \frac{\partial}{\partial x_{j}} (\varepsilon u_{j} u_{j}) = - \frac{\varepsilon}{\rho} \frac{\partial p}{\partial x_{j}} - \frac{\varepsilon}{\rho} \frac{\partial}{\partial x_{j}} \left( \eta \frac{\partial u_{j}}{\partial x_{j}} \right) + f_{p} + \varepsilon g \quad \text{........................................................(10)}
\]

\[
f_{p} = F_{p} \varepsilon u_{j} \quad \text{........................................................(11)}
\]

\[
F_{p} = \frac{\eta(1 - \varepsilon)}{\rho e} \left( 150(1 - \varepsilon) + 1.75 Re \right) \quad \text{........................................................(12)}
\]

\[
Re = \frac{\varepsilon pu_{th} D_{th}}{\eta} \quad \text{........................................................(13)}
\]

\[
\frac{\partial}{\partial t} (x_{j}^{2}) + \frac{\partial}{\partial x_{j}} (x_{j}^{2} \varepsilon u_{j}) = 0 \quad \text{........................................................(14)}
\]
The constitutive equations, Eqs. (9) through (13), were solved by the SOLA method, and then an assumption was made: it is that respective interfaces follow the balance indicated by Eq. (14); heights $h_{ij}$ in each phase, as shown in Eq. (16), are continuously present in descending order of density in a direction from the lower part toward the higher part; and the same phase is not separated into two more regions.

The discharge of the molten pig iron slag provides a taphole liquid-flow resistance equivalent to Eq. (5), as a pressure boundary condition of the taphole side, and, thus, is considered to be natural flow-out. Conditions for the calculation appear in Table 6.

The molten pig iron and slag tapping is started from the initial liquid level in Table 6; tapping slag is ended when the gas phase reaches the taphole; and simultaneously, tapping slag is started from the taphole at the opposite side (at 180 degrees from the previous taphole). Switching the taphole described above is repeated about 10 times, and a liquid level at each phase, when each phase becomes a steady state, is shown in Fig. 8. Figure 9 indicates the time variation of the amount when tapping slag.

Liquid-flow resistance increases as slag viscosity increases, and thereby, the curvature toward the taphole of the interface gas–slag liquid level increases during the latter half of the tapping. As a result, the time for tapping slag (the time until gas blowing) is reduced and, thereby, the slag residence amount in the furnace increases.

The increase of the in-furnace residence amount leads especially to an increase in the iron slag amount remaining immediately after an increase in the slag viscosity. Figure 10 illustrates the correlation between the slag amount remaining per day in the actual blast furnace (a slag charge amount—a discharge amount) and the estimated slag viscosity. In Fig. 10, typical time change of data is illustrated.

When the viscosity increases at state (a) and the remaining slag amount increases until state (b), normally, the remaining slag amount gradually decreases and returns to state (c) by a tapping slag operation, such as a reduction of the tapping time interval for molten pig iron.

Even under such taphole and operating conditions, slag viscosity affects the remaining slag amount. For the gradient of a calculation result shown in Fig. 10, it was found that the actual result and the tendency are very consistent, as well as the data obtained by EBF results, the tapping slag phenomenon, can be conducted as the fluidization phenomenon. In EBF, the influence of the crystallization temperature was not determined. (Fig. 6). In the actual blast furnace, there are a temperature distribution and a composition distribution in the furnace lower part and thus, some thought is needed on the influence on different regions, such as the distribution in the radial direction.

However, slag drainage can be considered basically to be a phenomenon subject to viscosity.

\[ h_{ij}' = \frac{x^2 V_{sk}}{S_0} \]  
\[ H_{ij} = \sum_{i} h_{ij}' \]  
(Einstein summation convention)

### Table 5. Calculated tap-hole diameter of EBF drainage flow analysis.

<table>
<thead>
<tr>
<th>Calculated tap-hole diameter (mm)</th>
<th>Frequency (TAP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32.5±37.5</td>
<td>8</td>
</tr>
<tr>
<td>37.5±42.5</td>
<td>8</td>
</tr>
<tr>
<td>42.5±47.5</td>
<td>9</td>
</tr>
<tr>
<td>47.5±52.5</td>
<td>7</td>
</tr>
<tr>
<td>52.5±57.5</td>
<td>0</td>
</tr>
<tr>
<td>57.5±62.5</td>
<td>1</td>
</tr>
</tbody>
</table>

### Table 6. Calculation condition.

<table>
<thead>
<tr>
<th>Properties of fluids</th>
<th>unit</th>
<th>Gas</th>
<th>Slag</th>
<th>Pig</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>kg/m³</td>
<td>1.2</td>
<td>2650</td>
<td>6800</td>
</tr>
<tr>
<td>Viscosity</td>
<td>poise</td>
<td>1.6×10⁴</td>
<td>5×10⁴</td>
<td>0.05</td>
</tr>
<tr>
<td>Initial liquid surface level</td>
<td>(m)</td>
<td>3.5</td>
<td>2.3</td>
<td>1.1</td>
</tr>
</tbody>
</table>

### Table 6. Calculation condition.

<table>
<thead>
<tr>
<th>Conditions</th>
<th>unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of taphole</td>
<td>-</td>
<td>2 (face each other)</td>
</tr>
<tr>
<td>Cross section of taphole</td>
<td>m²</td>
<td>0.124</td>
</tr>
<tr>
<td>Pressure in blast furnace</td>
<td>kPa</td>
<td>100</td>
</tr>
<tr>
<td>Liquid occupancy rate in cokeheal</td>
<td>-</td>
<td>0.35</td>
</tr>
<tr>
<td>Pig generation rate</td>
<td>kg/s</td>
<td>116</td>
</tr>
<tr>
<td>Slag rate</td>
<td>kg/pt</td>
<td>300</td>
</tr>
</tbody>
</table>
Hence, as illustrated in Fig. 7, although the high MgO content in high Al$_2$O$_3$ slag increases the crystallization temperature, the MgO content can be considered effective in slag drainage in a blast furnace operation.

4.2. Permeability Evaluation in the Lower Part of the Furnace

The consideration is conducted for the effect of slag properties on slag fluidity in the in-furnace dripping zone and the cohesive zone and the dripping properties in the in-furnace dripping zone and the cohesive zone, from the investigation by (1) dissecting EBF, (2) in-furnace samples in the operation of EBF, permeability evaluation results, (3) the molten slag dripping experiment in the coke-bed, (4) the softening melting test for sinter ore.

4.2.1. Sampling in the EBF and Investigation by Dissection

EBF comprises a cohesive zone sampler capable of sampling the contents, which are hung from the lower part of a shaft to the dripping zone, and a dripping zone sampler with 3 levels in the height direction in the dripping zone, which are capable of sampling in-furnace coke, ore, and molten materials, respectively.

In-furnace sampling results for each case and the results of the dissection are shown in Figs. 11 and 12. The dessec- 

tion was carried out under CASE 4 conditions in Table 4 after gas blowing off.

It can be estimated, based on the ratio of the presence of molten materials (Fig. 11(a)) and the distribution of reduction rates, that the cohesive zone in the operation is located between 0.75 to 2.2 m from the tuyere in the upper direction.

To perform the permeability evaluation for each height direction, the study focused on 3 regions in the furnace height direction of the dripping zone (between the tuyere and 0.75 m in height therein), the cohesive zone (the upper part of the tuyere between 0.75 m and 2.2 m in height therein), and the lumy zone (the upper part of the tuyere between 2.2 m and 4.5 m in height therein). In the cohesive zone, the reduction rate increases (Fig. 11(b)) and the molten materials appear in the ore layer. In the dripping zone, the molten materials are trapped between coke particles (Fig. 11(a)). Based on the C-concentration distribution (Fig. 11(d)) in the remaining metals, it can be estimated that dripping is begun by starting carbonization and progresses rapidly thereafter.

Also, the FeO slag falls to a tapping slag value level shortly after starting dripping (Fig. 11(e)).

It can be considered that, even if FeO remains in the slag when producing the initial melt, FeO is removed in a short time after dripping starts. Thus, the dipping slag is handled as a non-FeO system here.

The slag basicity, CaO/SiO$_2$, is at about 2.0, equivalent to that of sintered ore gangue mineral (Fig. 12(b)), but declines to nearly the discharging slag level of 1.4 in the dripping zone. Al$_2$O$_3$ also begins to rise in the upper part of the dripping zone (Fig. 12(a)), and thus, slagging the ash (SiO$_2$, Al$_2$O$_3$) derived from the tuyere begins in the dripping zone.

Figures 12(d) through 12(f) illustrate the expanded dripping zone and the distributions of slag of 1 500°C and slag crystallization temperature calculated from composition analysis. As the level declines in the blast furnace, Al$_2$O$_3$ increases and MgO decrease.

Thus, the viscosity at 1 500°C rises slightly as the furnace lowers, but stays in the range of about 1 to 3 poise until the tuyere level, because of a rise in temperature. Although the crystallization temperature fluctuates, there is little change in temperature in the upper tuyere of 0.4 m in
The influence of the amount of gas in each case in EBF, are used molten pig iron (derivation coke and coal ash materials) conducted.

The permeability evaluation is conducted in the dripping zone. In CASE 5, KRL is low. By analyzing the above with slag CaO/SiO$_2$, it is discovered that KRL increases as CaO/SiO$_2$ increases, as illustrated in Fig. 15. Hence, no effects of slag viscosity and crystallization temperature on KRL are found. However, a correlation between the CaO/SiO$_2$ slag and KRL was recognized.

4.2.3. Effects of Slag Properties on Permeability in the Dripping Zone

Figures 13 through 15 illustrate effects of typical slag composition on KRL in the dripping zone defined in the preceding section. Figure 13 illustrates the relationship between estimated slag viscosity and permeability in the dripping zone.

In CASE 2, the viscosity is relatively low; the crystallization temperature is high; the KRL is high; and the correlation between viscosity and permeable resistance is low. Thus, it is discovered that there is a tendency for the crystallization temperature to be high and KRL to be high.

Hence, Fig. 4 illustrates the effects of the difference between the temperature in the drip zone and the slag crystallization temperature, on permeability in the dripping zone. In CASE 1 through 4, KRL increases as the crystallization temperature approaches the temperature in the dripping zone. In CASE 5, KRL is low. By analyzing the above with slag CaO/SiO$_2$, it is discovered that KRL increases as CaO/SiO$_2$ increases, as illustrated in Fig. 15.

Hence, no effects of slag viscosity and crystallization temperature on KRL are found. However, a correlation between the CaO/SiO$_2$ slag and KRL was recognized.

(2) Evaluation for Slag Hold-up

To evaluate the slag properties affecting a pressure drop in the dripping zone, which includes not only viscosity and the crystallization temperature but also wettability, which CaO/SiO$_2$ is considered to be associated with, the slag dripping experiment was carried out in the coke-bed layer.

The coarse slag (Table 7) is continuously charged at a predetermined speed and the pressure drop for slag’s dripping time is measured, after the temperature increases to the predetermined temperature (between 1 450 and 1 550°C), while feeding each coke-bed layer (particle size: 8 to 10 mm, layer height: 140 mm) in a graphite crucible with a grate (70 mm/sq) in the order of lower part to upper part, to the bottom at a N$_2$ flow rate of 50 NL/min.

Here, the coarse slag is prepared by providing reagent regulation to the slag sampled in the actual blast furnace to pulverize the slag into that of −5 mm. Figure 16 illustrates the time variation of the pressure drop in the experiment.

After charging the slag, the slag powder dropped on the coke-bed layer are instantaneously dissolved. After several minutes, the dripping is started.

With the commencement of dripping, a nearly constant pressure is maintained after the pressure rises. After completing the charge, that state is continued for a while. The increases in pressures caused by the slag dripping are compared for each slag component. After completing the dripping, the amount of gas is decreased to 10 NL/min or lower while maintaining the temperature, and then the slag remaining in the crucible is dripped and thereafter cooled. The remaining dripping slag amount (including the amount remaining in the crucible) is volumetrically converted and made into a space occupying ratio to the coke-bed layer.

The evaluation is conducted as follows, in the order of the dripping zone and cohesive zone.

4.2.2. Permeability Evaluation Index in the Lower Part of the Furnace

For permeability evaluation lower part of furnace, absolute indexes, $K_{RL}$ and $K_{RM}$ that take into account the influence of the amount of gas in each case in EBF, are used for the dripping zone region and the cohesive zone region.

The evaluation of the gas permeability index, $K_{RL}$, in this case, is expressed by Eq. (17) with the following equation:

$$K_{RL,M} = \frac{\Delta P}{\Delta L} \left[ \frac{215}{(\Phi\alpha L/(1-\epsilon))} \mu^\beta \right]^{1/2}$$

The evaluation is conducted as follows, in the order of the dripping zone and cohesive zone.
actual measurement by the theoretical equation by Fukutake et al., the liquid hold-up is about 0.5 to 4.5%. Thus, the amount of slag remaining is equal to that of the static hold-up.

Hence, the possibility, that the surface tension and the contact angle are major factors, is high. Here, consideration is given to the effects of slag viscosity and crystallization temperature, which are objects to be evaluated, and thereafter, consideration is given to the surface tension and the contact angle.

Figure 18 illustrates the effects of slag viscosity and crystallization temperature. When the CaO/SiO$_2$ is constant and the viscosity increases, the pressure drop has an upward tendency. When the CaO/SiO$_2$ declines, the pressure drop largely decreases. The pressure drops differ, depending on CaO/SiO$_2$, even at the same (equal) crystallization temperature. The pressure drops cannot be classified only by the viscosity and crystallization temperature.

As illustrated in Fig. 19, under equal CaO/SiO$_2$, the rising width of the pressure drop, depending on lowering of the temperature, is wide in high Al$_2$O$_3$. However, under low CaO/SiO$_2$, the rising width is narrow even for high Al$_2$O$_3$. Further, Fig. 20 illustrates effects of the Al$_2$O$_3$ slag. In Fig. 20, the effects of MgO are not clear. However, if MgO is high and CaO/SiO$_2$ is low, the pressure drop is sufficiently small, even in high Al$_2$O$_3$.

Thus, for the pressure drop by dripping the coke-bed, it is found that the effect of CaO/SiO$_2$ is greater than that of viscosity or crystallization temperature. The results indicate the same tendency as the results (Figs. 13 through 15) in EBF that were described in the preceding section.

The phenomena mentioned above coincides qualitatively with the conventional tendency$^{11,21,22}$ which increases the dripping slag hold-up amount in the coke-bed as Al$_2$O$_3$ and CaO/SiO$_2$ (>$1.0$) increase.

For effects of slag composition on wettability with surface tension force and carbonaceous materials, although there are numerous reports, Ohgusu et al.$^{11}$ have pointed out that adhesive wet (non-dimensional interfacial tension $N_c$) as illustrated in the experiment by Fukutake et al.$^{9}$ is not dominant between slag and coke, but immersion wet ($N_c$cos $\theta$) is dominant.

Then, for the effects of wettability on the static hold-up obtained in Fig. 17, some thought is required. For the slag surface tension force, the estimative equation of Boni et al.$^{19}$ is employed, using a surface tension force coefficient $F_i$ of each oxide.

$$\gamma = \sum_i M_i F_i$$

Here, the surface tension force coefficients of each composition indicated in Table 8 are employed as $F_i$. Also, for the contact angle between coke and slag, there are a number of reports. For the blast furnace slag especially, the result is that, when CaO/SiO$_2$ is 1.5 or greater, the slag is little or not wetted with the coke and, when CaO/SiO$_2$ is 1.3 through 1.4 or smaller, a lower contact angle $\theta$ is obtained.

Thus, it appears that dripping slag in the blast furnace varying between about 2.0 to 1.2 is in the transitional phase of from a non-wetted system to a wetted system, and that CaO/SiO$_2$ is the key factor.

Here, for the contact angle with the slag and the carbonaceous material, the following equation holds, based on the measurement values prepared by Ohgusu et al.$^{11}$ and Mehta et al.$^{21}$.
The modified capillary number \( n^{11) \) taking into account the wet immersion was defined by the Eq. (20) as a non-dimensional number associated with the surface tension.

\[
\theta = \frac{2.79}{2.79 + 4.36(CaO/SiO_2 - 1.24)} \quad 1.25 < C/S < 1.49
\]

\[
\frac{C_{pm}}{\gamma (\cos \theta)}
\]

Equations (18), (19) are assigned to Eq. (20) and the relationship with the static hold-up \( h_{sp} \) is illustrated in Fig. 21. Nearly negative correlation is obtained from the relationship and the following equation holds.

\[
h_{sp} = 44.1 \cdot C_{pm}^{0.77}
\]

To compare the above, the results prepared by Ohgusu et al. \( 11) \) are illustrated in Fig. 21. They show very similar correlation.

Then, in estimating the static hold-up in the dripping zone in EBF from the Eq. (21), the hold-up is about 3–4%. It is found that the relationship with the permeable resistance index \( K_{RL} \) is correlated positively, as illustrated in Fig. 22.

Thus, in the blast furnace slag composition range of the study, the permeability in the lower part of blast furnace appears to be more affected by the wettability, such as the surface tension and contact angle due to CaO/SiO\(_2\) changes than by the slag viscosity (Fig. 13).

### 4.2.4. Effects of High Al\(_2\)O\(_3\) Sintered Ore on Permeability in the Cohesive Zone

The evaluation is conducted to determine the effects of high temperature characteristics of Al\(_2\)O\(_3\) sintered ore used in EBF on the permeable resistance in the cohesive zone. Figure 23 illustrates the softening-melting test results of high Al\(_2\)O\(_3\) sinter. For the sinter ore KS value expressed by the temperature-integrated value of the permeable resistance index, the rising width of the KS value to the increase of sintered Al\(_2\)O\(_3\), as described by the conventional knowledge and published data, \( 15) \) is small. In particular, sintered ore B has a lower KS value than that of BASE (Table 2), because of high MgO. Figure 24 compares KS actual values for various kinds of conventional sintered ores with the value \( 15) \) estimated from the composition to show the comparison. According to Fig. 24, it is understood that a higher Al\(_2\)O\(_3\) of the sintered ore does not always increase the KS value, and even when Al\(_2\)O\(_3\) is high by other component adjustments, the KS value can be decreased. The permeable resistance in the cohesive zone is defined from the investigation results by dissection in the preceding section. Effects of the sintered ore KS on \( K_{RL} \) (Eq. (18)) defined from the permeable resistance in the cohesive zone are illustrated in Fig. 25, together with the operation data in the existing report \( 14) \) from EBF. It has been confirmed that the permeable resistance \( (K_{RL}) \) in the cohesive zone depends on the sintered ore KS value. \( 14) \) That is, even when Al\(_2\)O\(_3\) sintered ore is high, the permeability in the cohesive zone can be maintained by suppressing an increase of the KS value, as well as when the MgO is high.

### 5. Conclusion

In order to conduct a systematic evaluation for the effects of Al\(_2\)O\(_3\) concentration in the slag on the blast furnace operation, which is focused on slag drainage for each in-furnace area and permeability in the lower part of blast furnace, from the viewpoint of slag fluidity, a high Al\(_2\)O\(_3\) slag operation test (slag Al\(_2\)O\(_3\) 20%) in the experimental blast furnace was carried out. The following knowledge and data were obtained.

1. The slag drainage phenomenon in the furnace hearth is a fluidization phenomenon dominated by viscosity. The slag drainage rate decreases as the slag viscosity increases. Thus, to maintain slag drainage under high Al\(_2\)O\(_3\), for instance, an increase of the MgO concentration in the slag is effective. Also, in this experiment range, the effects of the slag crystallization temperature on the slag drainage rate are relatively small in comparison to the effects of viscosity.

2. The pressure drop in the dripping zone increases as...
the Al\(_2\)O\(_3\) concentration in the slag increases. Even if the CaO/SiO\(_2\) increases, the pressure drop in the dripping zone increases. The pressure drop is mainly caused by the effect of wettability as a result of the slag static hold-up, and little due to the effects of dripping slag viscosity and crystallization temperature. In the high Al\(_2\)O\(_3\) concentration slag, to suppress the increase of the pressure drop in the dripping zone, it is effective that the decrease of the hold-up by the increase of MgO in the slag and slag drainage and permeability. It was determined that the pressure drop in the dripping zone, blast furnace design that increases MgO in the slag and slag drainage and permeability, it was determined that each area in the furnace were investigated and systematically evaluated. As a result, in order to properly maintain slag drainage and permeability, it was determined that the blast furnace design that increases MgO in the slag and decreases CaO/SiO\(_2\) in the slag is effective.

### Nomenclature

\(\eta, \eta^\prime, \eta^\prime\prime\) \(\eta^\prime, \eta^\prime\prime\) : Viscosity at 1\,500°C 
\(T, T^\prime\) : Slag-crystallization temperature (°C) 
\(X\) : Weight ratio of slag composition X (wt%) 
\(u, u_0\) : Superficial velocity of liquid (m/s) 
\(P\) : Pressure (Pa) 
\(F_{\text{diss}}\) : Dissipation term by pressure drop (J/m\(^3\)) 
\(L\) : Length of flow (m) 
\(D_{\text{sl}}\) : Tap hole diameter (m) 
\(f\) : Friction coefficient in the taphole (→) 
\(A, A_i\) : Cross section of cell (m\(^2\)) 
\(h\) : Height (m) 
\(\Delta P\) : Pressure drop (Pa) 
\(\rho\) : Density of liquid (kg/m\(^3\)) 
\(Re\) : Reynolds number (→) 
\(\varphi\) : Taphole interior surface roughness (m) 
\(i, j, k\) : Component of coordinate (k: height) 
\(l\) : Each phase (metal, slag, gas) 
\(x, y, z\) : Each component (i-component) 
\(R, R_i\) : Thickness of each phase (m) 
\(H, H_i\) : Height of each phase (metal, slag) 
\(U_o\) : Volume of each (m\(^3\)) 
\(S_o\) : Cross section of cell (m\(^2\)) 
\(u\) : Velocity of each phase (metal, slag) 
\(\alpha, \theta\) : Void fraction (→) 
\(f_d\) : The drag coefficient (1/4) 
\(d_p\) : Particle diameter (m) 
\(K_R\) : Permeable resistance index of the dripping zone (1/m) 
\(K_{RM}\) : Permeable resistance index of the cohesive zone (1/m) 
\(\phi\) : Shape co-efficient (→) 
\(M_i\) : Hight (m) 
\(g\) : Gravitational constant (→) 
\(\mu\) : Viscosity of gas (kg/m/s) 
\(p_o\) : Density of gas (kg/m\(^3\))

### REFERENCES


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