Evaluation of Sinter Quality for Improvement in Gas Permeability of Blast Furnace

Naoyuki TAKEUCHI,1)* Yuji IWAMI,2) Takahide HIGUCHI,2) Koichi NUSHIRO,2) Nobuyuki OYAMA2) and Michitaka SATO2)

2) Steel Research Laboratory, JFE Steel Corp., 1 Kokan-cho, Fukuyama, Hiroshima, 721-8510 Japan.

(Received on September 3, 2013; accepted on December 2, 2013; originally published in Tetsu-to-Hagané, Vol. 99, 2013, No. 7, pp. 448–457)

In the recent operation of blast furnace, it is supposed that high gas permeability of burden is important for low RAR and high PCR operation. In this work, sinter quality for improvement in gas permeability of blast furnace was investigated with reduction degradation and under-load-reduction tests. As the results, the reduction degradation of sinter is deteriorated by increasing H2 concentration in the reduction gas under the condition of below 3.8 vol% H2. However, over 3.8 vol% H2, increase of H2 has no effect on the reduction degradation because the diffusion of reduction gas in the sinter is limited. On the other hand, from the under-load-reduction test, there is possibility that increase in H2 concentration of reduction gas and decrease in slag ratio in sinter are effective to improve gas permeability of lower part of blast furnace rather than reducibility of sinter. Due to adoption of these experimental results to a 2-dimensional mathematical simulation model, the precision of pressure drop calculation of blast furnace was improved. It is considered from the evaluation by this model calculation that the RDI, a slag ratio and the slag viscosity as the sinter properties are greatly influence on the permeability of blast furnace.

KEY WORDS: sinter; blast furnace; PCR; gas permeability; H2; RI; RDI; slag.

1. Introduction

Although production flexibility has been demanded in blast furnaces in recent years in order to cope with changing steel demand, low coke rate (CR) operation technology is a constant challenge. In response to the sharp rise in the prices of raw materials, steel makers have actively promoted high pulverized coal rate (PCR) operation with the aim of reducing CR and realizing cost reductions by increased use of low grade raw materials. However, these changes in blast furnace operation have also had various negative effects, such as deterioration of gas permeability in the blast furnace and an increase in the slag ratio. In particular, because improvement of gas permeability in the blast furnace is critical for maintaining the productivity of iron and blast volume, it is necessary to control total gas permeability from the top to the bottom of the furnace in regular operation.

The properties of sintered iron ore affect gas permeability in the blast furnace. As representative properties for sinter, the reduction degradation index (RDI) for permeability in the upper part of the furnace, and the S value1) and the KS value2) for permeability in the lower part of the furnace may be mentioned. High RDI sinter deteriorates gas permeability in the upper part of the blast furnace because the particle size of the sinter is easily reduced by reduction degradation (powdering) in the furnace. In the lower part of the furnace, the sinter reducibility index (RI), RDI, tumble index (TI), gangue content $V_g$, and gangue melting point $T_{mg}$ influence the KS value. Effects of these indexes have been reported, and it is thought that high RI sinter improves gas permeability in the lower part of the blast furnace. For this reason, sinter with low RDI and high RI is considered to be appropriate for improving gas permeability in the blast furnace. However, RDI tends to increase when RI is high. Against this background, various research3–7) on quality management indexes for sinter have been carried out to date, but few previous studies have attempted to evaluate permeability from the upper part to the lower part of the furnace in an integrated manner.

On the other hand, gases containing H2, such as Liquefied Natural Gas (LNG) and others, are expected to be effective in improving gas permeability and reducing CO2 in blast furnaces.8) However, many uncertainties still remain in connection with the effect of these H2-containing gases on blast furnace gas permeability.

Therefore, in the present research, the authors reproduced the atmosphere in the blast furnace during high PCR operation and in operation with hydrogen gas (LNG, H2) in order to investigate the effects of sinter quality and reducing gas composition on RDI and softening under load, in terms of pressure drop. Based on the results of these experiments, we attempted to improve the accuracy of the conventional simulation model and studied the appropriate sinter quality for
improvement of gas permeability in the blast furnace.

2. Experimental Method

2.1. Sinter Properties and Reducing Gas Conditions Used in Experiments

In order to evaluate the effect of sinter properties on gas permeability in the blast furnace, four types of sinter (A)–(D) with different RI, RDI, and chemical compositions were used. Sinters (A)–(C) were produced by actual sintering machines with different operating conditions, and sinter (D) was prepared with a laboratory-scale experimental sintering machine simulating the Hybrid Pelletized Sinter (HPS) process\(^9,10\) and contains 40 wt% of pellet feed with a high T.Fe content. Table 1 shows the chemical composition, JIS-RI,\(^11\) and JIS-RDI\(^12\) of sinters (A)–(D). Here, JIS-RI and JIS-RDI refer to the reducibility index (RI) and reduction degradation index (RDI) as measured in accordance with the applicable JIS standards, respectively. Hereinafter, these are abbreviated as JIS-RI and JIS-RDI.

In this research, reduction degradation experiments and softening under-load experiments were conducted in order to investigate the effects of sinter properties and H\(_2\) gas on gas permeability in the blast furnace. In the reduction degradation experiments, permeability in the lumpy zone in the upper part of the furnace was evaluated, and in the under-load experiments, permeability in the cohesive zone in the lower part was evaluated.

In order to evaluate these effects under the conditions supposed to exist in actual operation, the temperature and gas atmosphere were calculated from a 2-dimensional model of the blast furnace\(^13,14\) as sinter reduction conditions, and were specified as shown in Fig. 1. Four species of gas were used in the experiments, N\(_2\), CO, CO\(_2\), and H\(_2\). The H\(_2\) concentration was controlled in the range of 2.7–9.0 vol\%, and the mean H\(_2\) concentration was adjusted to 3.8, 4.8, 5.8, or 6.8 vol\% to correspond to the H\(_2\) atmosphere in the blast furnace at PCR of 80, 120, 160, or 200 kg/t-pig. The gas composition which was set in the experiments was made to change over time in order to reproduce the reduction condition of the sinter in the blast furnace. The mean concentration of H\(_2\) was the mean value from the tuyere level to the furnace top as calculated by the 2-dimensional blast furnace model. Although H\(_2\)\(_2\)O gas is thought to exists in blast furnaces, there are still many unknown points regarding the effect on reduction degradation.\(^15\) Therefore, H\(_2\)O was not considered in this study. Table 2 shows the calculation conditions of the 2-dimensional blast furnace model. In the model, productivity of 2.2 t/m\(^3\)-day and RAR of 500 kg/t-pig were assumed, and the properties of the sinter and coke burden materials were held constant. Under these conditions, PCR was changed to 80, 120, 160, or 200 kg/t-pig, and the changes over time in the gas composition and temperature in the furnace were calculated. Although the same can also be said about actual blast furnace operation, because increasing PCR under constant RAR means replacing high calorie lumpy coke with low calorie pulverized coal, the heat input to the furnace is inadequate, and as a result, the temperature of the molten pig iron decreases. Furthermore, there is also a decrease in the heat flow ratio, which has a large influence on RDI and softening under-load of sinter. However, in this report, the heat pattern in the experiments was held constant in order to clarify the effects of the H\(_2\) gas concentration on the RDI and softening under-load behavior of the sinter. In this case, the oxygen enrichment ratio in

![Fig. 1. Experimental reducing conditions determined with 2-dimensional mathematical simulation model of blast furnace.](image-url)

### Table 1. Specification of tested samples.

<table>
<thead>
<tr>
<th></th>
<th>T.Fe (%)</th>
<th>FeO (%)</th>
<th>SiO(_2) (%)</th>
<th>CaO (%)</th>
<th>Al(_2)O(_3) (%)</th>
<th>MgO (%)</th>
<th>Slag total (%)</th>
<th>CaO/SiO(_2) (%)</th>
<th>JIS-RI (%)</th>
<th>JIS-RDI (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sinter (A)</td>
<td>56.14</td>
<td>7.73</td>
<td>5.13</td>
<td>10.75</td>
<td>2.09</td>
<td>1.28</td>
<td>19.25</td>
<td>2.10</td>
<td>72.1</td>
<td>33.6</td>
</tr>
<tr>
<td>Sinter (B)</td>
<td>56.07</td>
<td>9.48</td>
<td>5.28</td>
<td>10.23</td>
<td>2.21</td>
<td>1.66</td>
<td>19.38</td>
<td>1.94</td>
<td>66.8</td>
<td>29.1</td>
</tr>
<tr>
<td>Sinter (C)</td>
<td>58.95</td>
<td>10.19</td>
<td>3.71</td>
<td>9.19</td>
<td>1.46</td>
<td>1.37</td>
<td>15.73</td>
<td>2.48</td>
<td>60.5</td>
<td>26.5</td>
</tr>
<tr>
<td>Sinter (D)</td>
<td>59.70</td>
<td>8.94</td>
<td>4.04</td>
<td>8.75</td>
<td>1.49</td>
<td>0.82</td>
<td>15.10</td>
<td>2.17</td>
<td>69.0</td>
<td>31.4</td>
</tr>
</tbody>
</table>
blast furnace operation is increased in the range of 1.0–7.0 vol%\(^{16)}\), which is equivalent to keeping the molten iron temperature and heat flow ratio at constant levels.

Regarding temperature changes in the blast furnace, although it has long been known that a thermal reserve zone exists in the blast furnace\(^{17)}\), temperature holding at around 1,000°C, assuming a thermal reserve zone, was not performed in these experiments, as shown in the lower part of Fig. 1(a). The temperature changes in the blast furnace radial position (e.g., \(r/R = 0.05, 0.55, 0.95\)) calculated by the model and the heat pattern set in these experiment are shown in the upper part of Fig. 1(a). A thermal reserve zone can also be observed at each of the radial positions in the results calculated with the model. However, in order to reproduce the average temperature change of sinter charged to the blast furnace, in these experiments, weighted averages were obtained from the temperatures at 10 locations at each radial position \(r/R = 0.05, 0.15\) to 0.95 (–) and the existence ratio of solids at those positions, and as a result, this calculation gave a heat pattern without no thermal reserve zone.

### 2.2. Effects of Sinter Properties and H\(_2\) Concentration on RDI in Lumpy Zone

In order to investigate the effects of sinter properties and H\(_2\) concentration on RDI, a reduction degradation experiment simulating the atmosphere in the blast furnace was performed. The test materials used in the experiment were sinter (A)–(D) described above. The size of the sinter was 15.0–19.0 mm.

**Figure 2** shows a schematic illustration of the experimental apparatus. The apparatus comprises a 3-section electric furnace, reaction tube, gas preheating furnace, and gas mixing device. The reaction tube was made of alumina (inner diameter: 50 mm, length: 1,500 mm), and was set in the vertical position. At this time, the temperature range in the soaking zone was controlled to \(\pm 15^\circ\)C under a gas flow from the bottom to the top. The length of the soaking zone was 300 mm at 1,000°C.

In the experiment, a 600 g specimen filled in a platinum cage was placed in the center of the soaking zone, and was reduced at the predetermined temperature and gas composition, as shown in Fig. 1. The gas flow rate was set at 15 L/min. To evaluate reduction degradation in the heating-up process, the experiments were interrupted at 200, 400, 600, 800, and 1,000°C. On reaching the target temperature, the reducing gas was replaced with N\(_2\) and the specimen was cooled. In accordance with the reduction degradation test proposed by Iwanaga et al.\(^{3)}\), sample (500 g) was taken from the test specimen, rotated 900 times in a rotating drum (inner diameter: 130 mm, length: 200 mm, speed: 30 rpm) at room temperature, and the particle size distribution was measured. This reduction degradation test was performed three times with each sinter, gas composition and reducing temperature. In the figure showing the test results, which will be discussed in the following, the mean values are shown by plots, and the other values are shown as error bars.

### 2.3. Effects of Sinter Properties and H\(_2\) Concentration on Softening Under-Load in Cohesive Zone

In order to investigate the effects of sinter properties and H\(_2\) concentration on softening under-load behavior, an under-load reduction experiment which simulated the atmosphere in the blast furnace was performed. The test materials used in this experiment were the four sinters (A)–(D). The size
of the sinters was 4.8–6.7 mm.

Figure 3 shows a schematic illustration of the experimental apparatus, which comprises an electric furnace, reaction tube, load generating device, gas preheating furnace, gas mixing device, and gas analyzer. The furnace is a shaft-type (vertical) electric furnace in which a graphite heater is used, and the reaction tube is made of alumina (inner diameter: 80 mm, length: 1 000 mm). The crucible is made of carbon (inner diameter: 65 mm). A hole (inner diameter: 6.7 mm) was made in the bottom of the crucible in order to pass the gas and molten material through the tube. The moving weight-type load generating device at the top has a structure in which loading is applied to the specimen by way of a carbon rod, and enables simultaneous loading and measurement of the change in the height direction due to softening and melting of the sinter. The soaking zone temperature was controlled in the range of ±15°C under a gas flow, and the length of the zone was 50 mm at 1 650°C.

In this experiment, specimen (100 g), which had been filled in the crucible, was set in the center of the soaking zone, and was reduced at the predetermined temperature and gas composition while applying loading. The gas flow rate was set at 6 L/min. In the blast furnace, water gas reaction \((C + H_2O = CO + H_2, C + 2H_2O = CO_2 + 2H_2)\) and water gas shift reaction \((CO + H_2O = CO_2 + H_2)\) are conceivable.\(^{18,19}\) Therefore, in 2-D blast furnace model, the change of gas compositions is considered reflecting these reactions. A heating temperature of 1 650°C was used in order to evaluate the behavior of the sinter up to softening, melting, and dripping. After completion of the experiment, the reducing gas was replaced with \(N_2\) gas and the specimen was cooled. The specimen recovered after the experiment was separated into molten pig iron and slag, and chemical composition analysis was performed. The under-load reduction experiment was performed three times under each sinter and gas composition condition. The mean values are plotted in the figure showing the test results, which will be discussed in the following, and the other values are shown as error bars.

3. Experimental Results

3.1. Effects of Sinter Properties and \(H_2\) Concentration on RDI

In this report, the reduction of the particle size of the sinter due to reduction degradation was evaluated using the calculated mean particle size after the reduction degradation experiment following the method proposed by Iwanaga et al.\(^{9}\) Figure 4(a) shows the relationship between the mean particle size of the tested samples and the reduction rate after the reduction degradation experiment with sinters (A)–(D) under the condition of a mean \(H_2\) concentration of 5.8 vol%.

The particle size of all four sinters decreased as the temperature increased and reduction proceeded. The decrease in mean particle size was particularly remarkable in the reduction temperature range from 400°C to 600°C. However, particle size reduction became stagnant when the reduction temperature exceeded 600°C. Figure 4(b) shows the relationship between the mean particle size after the reduction degradation experiment at 1 000°C and the JIS-RDI of the sinters. The particle size decrease became more moderate as JIS-RDI decreased. The same tendencies were also observed under the other \(H_2\) concentration conditions.

Figure 5(a) shows the relationship between the mean particle size of sinter (A) after the reduction degradation experiment under conditions of mean \(H_2\) concentrations of 3.8, 4.8, 5.8, and 6.8 vol%.

From this figure, the decrease of the mean particle size of the sinter is approximately the same, independent of differences in the \(H_2\) concentration. In the figure, the results of a reduction degradation experiment performed with \(N_2–CO\) mixed gas are also plotted. The \(H_2\) concentration at the mean \(H_2\) concentration of 5.8 vol% is converted to \(CO\) concentration so that the molar equivalents are identical. Here, a mean \(H_2\) concentration of 5.8 vol% means the average gas composition from the furnace top to the tuyere level is 49.2 vol% \(N_2\)-33.2 vol% \(CO\)-11.8 vol% \(CO_2\)-5.8% \(H_2\). When \(H_2\) is converted to \(CO\), this becomes 46.4 vol% \(N_2\)-42.4 vol% \(CO\)-11.2 vol% \(CO_2\)-0% \(H_2\). In comparison with the condition when the reducing gas contains \(H_2\), reduction degradation is depressed in reduction by \(N_2–CO\). From this, it can be understood that \(H_2\) has a large influence on reduction degradation.

Figure 5(b) shows the relationship of the mean particle size of the sinter after the reduction degradation experiment at 1 000°C and the mean \(H_2\) concentration in the reducing gas. As the \(H_2\) concentration increases, the mean particle size of the sinter decreases in the \(H_2\) concentration range between 0 vol% and 3.8 vol%. However, the \(H_2\) has little effect on reduction and degradation in the mean concentration range from 3.8 vol% to 6.8 vol%.
3.2. Effects of Sinter Properties and H₂ Concentration on Softening Under-Load

Figure 6(a) shows the relationship between pressure drop and sinter temperature in the under-load reduction experiments with sinters (A)–(D) under the condition of a mean H₂ concentration of 5.8 vol%. The maximum value of pressure drop shows the largest value with sinter (A), which has a high JIS-RDI, followed by (B) and (C). However, sinter (D), which has a higher JIS-RDI than sinters (B) and (C), showed the smallest value of pressure drop. With sinter (C), which has the smallest JIS-RDI, the progress of dripping was retarded, even though softening and melting occurred, and the molten sinter stagnated in the crucible until around 1500°C.

Next, Fig. 6(b) shows the relationship between pressure drop and the sinter temperature in the under-load reduction experiment with sinter (A) under conditions of mean H₂ concentrations of 3.8, 4.8, 5.8 and 6.8 vol%. The maximum value of pressure drop with sinter (A) decreased as the concentration of H₂ increased. The temperature at which sinter melting started also shifted to the high temperature side, and the temperature at which dripping was completed shifted to the low temperature side as the H₂ concentration increased.

4. Discussion

4.1. Effects of Sinter Properties and H₂ Concentration on Reduction Degradation

In this research, in order to clarify the effect of H₂ concentration on reduction and degradation of sinter under conditions simulating the gas atmosphere in the blast furnace, the effect of sinter properties was investigated with four different types of sinter by adjusting the H₂ concentration in the reducing gas. In the results in Fig. 4(a), the decrease in the mean particle size of the tested sinters was remarkable in the temperature range from 400°C to 600°C. This is in agreement with the report by Iwanaga et al. 3) in which reduction rate decrease. These findings are generally consistent with the results of the present experiments. Therefore, using the method proposed by Sakamoto et al. 20) a Weibull 21) analysis of cracks in the sinter was performed in order to confirm this tendency from the viewpoint of sinter destruction behavior.

In the Weibull analysis, samples were taken from the sinter after reduction but before the reduction degradation experiment. The fracture surfaces were observed, and 100 cracks in each particle were selected at random. The lengths of these cracks were measured, and the probability density function (PDF) was obtained. In cases where the probability of distribution of the crack lengths followed the Weibull distribution, the mode value xₘ (μm) was obtained using the following Eqs. (1)–(3).

\[
\log[-\ln(1-G(x))] = \log\beta + m \cdot \log x \quad \ldots \ldots \ldots (1) \\
G(x) = \frac{m}{\beta} x^{m-1} \exp(-\beta x^m) \quad \ldots \ldots \ldots (2) \\
x_m = (1/\beta)^{1/m} (1-1/m)^{1/m} \quad \ldots \ldots \ldots (3)
\]

where, \(G(x), \beta, m, x, g(x)\) are \(G(x)\): cumulative distribution function, (-), \(\beta\): constant, (-), \(m\): Weibull coefficient, (-), \(x\): crack length (μm), and \(g(x)\): probability density function (-), respectively.

Figure 7 shows the results of the Weibull analysis. Comparing Case 1 through Case 3, in which the final reduction temperatures are different (200–600°C), the mode value \(x_m\) of sinter (A) increases. At 200°C, the main type of cracks is minute cracks with a size on the order of several 10 μm. However, as the temperature increases and reduction progress, crack generation and growth occur, and when the reduction temperature reaches 600°C, the sinter contains a large number of cracks with lengths of around 800 μm.

![Fig. 6. Experimental results of under-load-reduction test.](image)

![Fig. 7. Effect of reduction temperature and gas condition to crack distributions in sinter (A).](image)
Comparing Case 2 (400°C) and Case 3 (600°C), the increase in the mean value $x_m$ is remarkable. This is consistent with the decreasing tendency in the mean particle size seen in Figs. 4(a) and 5(a). Next, comparing the two conditions of Case 3 (mean H$_2$ concentration: 5.8 vol%) and Case 4 (mean H$_2$ concentration: 3.8 vol%), in which the H$_2$ concentrations are different, the mode value $x_m$ is substantially the same; that is, no effect of the H$_2$ concentration can be observed. Furthermore, comparing Case 3, in which the reducing gas contains H$_2$, and Case 5, i.e., reduction with N$_2$–CO, the mode value $x_m$ is higher in Case 3. Thus, the tendencies in the reduction degradation experiments and the Weibull analysis are in good agreement. As regards the H$_2$ concentration, although the crack length increases and reduction and degradation progress in the range up to 3.8 vol%, when the mean H$_2$ concentration is in the range of 3.8–6.8 vol%, the effect of the H$_2$ concentration on crack length is considered to be slight, and as a result, reduction degradation also does not progress. Concerning the condition of crack initiation in sintered structures, Inazumi et al. noted that, in a mixed structure consisting of skeletal rhombohedral hematite and a crystal encapsulating substance (magnetite, calcium ferrite, and silicate-type slag), cracks are readily initiated due to the difference in expansion resulting from the different reduction rates of the two substances. Here, Fig. 8 shows a cross-sectional photograph after reduction under the condition of Case 3 (mean H$_2$ concentration: 5.8 vol%). In this test, skeletal rhombohedral hematite and a crystal encapsulating substance exist in a mixed state in the region where large cracks with lengths of around 800 μm occurred, which is in agreement with the report by Inazumi. Moreover, Sakamoto et al., who carried out reduction degradation tests with N$_2$–CO gas, performed an analysis with crack lengths in the region of several 10 μm, whereas, in the present experiment, numerous coarse cracks of around 800 μm were observed. Because H$_2$ gas, which has a faster reduction rate than CO, was used as the reducing gas in these experiments, it may be conjectured that the difference in the length of the generated cracks was due to an increased difference in expansion between the skeletal rhombohedral hematite and the crystal encapsulating substance during reduction.

Next, in order to elucidate the reduction mechanism of H$_2$, a reduction rate analysis was performed for an unreacted core model, which is the reaction mode in Eqs. (4) and (5).

$$\text{Fe}_2\text{O}_3(s) + 3\text{H}_2(g) = 2\text{Fe}(s) + 3\text{H}_2\text{O}(g) \quad \cdots (4)$$

$$\text{Fe}_2\text{O}_3(s) + 3\text{CO}(g) = 2\text{Fe}(s) + 3\text{CO}_2(g) \quad \cdots (5)$$

Here, in order to discuss the influence of H$_2$ concentration on the change of sinter size at the temperature zone promoting the reduction degradation, an isothermal reduction experiment was conducted setting a reduction temperature of 600°C, reduction time of 3 hr, and gas compositions with mean H$_2$ concentrations of 3.8, 4.8, 5.8, and 6.8 vol%. The chemical reaction constant, effective diffusivity were evaluated by mixed control plot based on un-reacted core model. Apparatus and gas condition were the same as Figs. 1 and 2. Figure 9 shows the effective diffusion coefficient $D_e$ calculated by the unreacted core model. In reduction with the mean H$_2$ concentrations of 3.8, 4.8, 5.8, and 6.8 vol%, the effective diffusion coefficient $D_e$ increases in all cases in comparison with N$_2$–CO reduction. However, when the mean H$_2$ concentration was more than 3.8 vol%, no effect of the H$_2$ concentration on $D_e$ could be observed. In a study on the effect of H$_2$ addition in CO reduction of sinter, Ishii et al. reported that the reduction-suppressing effect was observed at 450–600°C and the reduction-promoting effect was observed at 600–800°C. It is thought that this appears as a reduction-promoting effect under the condition of a mean H$_2$ concentration of 3.8 vol% or less in the present paper. Moreover, based on the results of the above-mentioned analysis, it is estimated that reducing gas diffusion becomes the rate-controlling step in the H$_2$ concentration region of mean H$_2$ concentrations over 3.8 vol%. From the foregoing discussion, it can be conjectured that reduction degradation is encouraged by the increased crack length in the sinter in the region where the mean H$_2$ concentration is 3.8 vol% or less, because increases in H$_2$ concentration accelerate internal diffusion of the reducing gas in the sinter, whereas, in the H$_2$ concentration region above 3.8 vol%, diffusion of the reducing gas in the sinter becomes the rate-controlling step, and crack initiation and growth are stagnant.

### 4.2. Effects of Sinter Properties and H$_2$ Concentration on Softening Under-Load

When the furnace atmosphere in high PCR operation is considered, formation of low melting point slag containing FeO is depressed and high temperature properties are improved because the reduction potential increases and the
reduction rate in solid state improves.\textsuperscript{5} Therefore, focusing on the effect of JIS-RI in the furnace atmosphere simulating high PCR operation in the results of these experiments, in Fig. 6(a), sinter (A), which has a high JIS-RI, displayed the largest maximum value of pressure drop, and pressure drop then decreased in the order of (B), (C), and (D). Hence, the effect of JIS-RI was not clear. On the other hand, in Fig. 6(b), the maximum value of pressure drop decreases as the H\textsubscript{2} concentration increases, and it was conjectured that this is due to an increase in the reduction rate in solid state.

Moreover, since it is also conceivable that factors other than reducibility have large effects, the effect of the slag component was studied. It is known that FeO has a large effect on the viscosity of slag; however, the FeO content in slag during dripping is on the order of several \(\%\).\textsuperscript{25} Likewise, the FeO content in the slag after dripping was about 0.2–0.5\%. Therefore, the results were arranged assuming that the effect of FeO on slag viscosity is negligible. Figure 10(a) shows the relationship between the maximum value of pressure drop in the softening under-load experiment under the condition of a mean H\textsubscript{2} concentration of 5.8 \textit{vol}%, and the slag percentage as the total of SiO\textsubscript{2}, Al\textsubscript{2}O\textsubscript{3}, CaO, and MgO in the specimens. Pressure drop during softening and melting of the sinter increases as the slag percentage increases. On the other hand, Fig. 10(b) shows the relationship between the maximum value of pressure drop in the softening under-load experiment and the slag viscosity\textsuperscript{26} at 1500\(\degree\)C, as calculated using the chemical composition of the slag that dripped after the softening under-load experiment. The viscosity of a CaO–SiO\textsubscript{2}–Al\textsubscript{2}O\textsubscript{3}–MgO system slag which has softed and melted is high, at 0.2–32 Pa s\textsuperscript{27} in comparison with the viscosity of 3–8 \(\times\) 10\textsuperscript{–3} Pa s of Fe–C alloys,\textsuperscript{28,29} and it is known that permeability in the bottom of the blast furnace deteriorates when slag viscosity is high.\textsuperscript{28,29} The temperature at maximum pressure drop at under-load-reduction test as shown in Fig. 6 corresponds to that of the bottom of cohesive zone, near 1 300\(\degree\)C. As shown in Fig. 10(b), in the case of high viscosity slag, pressure drop were high. Therefore, it was presumed that the pressure drop of cohesive zone showed a good relation with viscosity of slag calculated at 1 500\(\degree\)C condition. The results of the present experiment also confirmed a tendency in which pressure drop increases when slag viscosity is high, assuming a condition where the amount of slag is approximately the same.

4.3. Effects of Sinter Properties and H\textsubscript{2} Concentration on Melting Initiation Temperature and Dripping Finish Temperature

The thickness of the cohesive layer is a conceivable factor controlling the gas permeability in the lower part of the furnace. Therefore, in this research, the melting initiation temperature \(T_i\) and the dripping finish temperature \(T_f\) were defined for the results obtained from the softening under-load experiment, referring to the S value,\textsuperscript{11} and the effect of sinter properties and the H\textsubscript{2} concentration on \(T_i\) and \(T_f\) were studied. Here, the melting initiation temperature \(T_i\) was defined as the temperature at which the shrinkage ratio of the specimen in the crucible reached 5\%, and the dripping finish temperature \(T_f\) was defined as the temperature at which the shrinkage ratio achieved 95%. The shrinkage ratio means the percentage change in the specimen layer thickness measured during the softening under-load test. When loading is applied to the specimen in the experiments, sliding of the specimen and holdup of the melt due to drag resistance of the gas were observed. The initial range of 0–5\% shrinkage and the final range of 95–100\% shrinkage were excluded from the evaluation to enable an accurate evaluation of the change in specimen height due to softening and melting of the sinter. Figure 11(a) shows the relationship between the melting initiation temperature \(T_i\) and the dripping finish temperature \(T_f\) obtained in the softening under-load experiment and the JIS-RI of sinters (A)–(D). The melting initiation temperature \(T_i\) was substantially constant and showed no correlation with JIS-RI. Likewise, the dripping finish temperature \(T_f\) showed no correlation with JIS-RI.\textsuperscript{30} Figure 11(b) shows the relationship between the FeO concentration in sinter reduced up to a temperature of 1 000\(\degree\)C under the condition of a mean H\textsubscript{2} concentration of 5.8 \textit{vol}%, and the JIS-RI of sinters (A)–(D). The FeO concentration in the sinter shows a correlation with JIS-RI, and was lowest in sinter (A) and highest in sinter (C).\textsuperscript{30} Hatano et al.\textsuperscript{30} showed that the softening resistance of sinter is greatly affected by the content of residual FeO, which reduces the melting point of slag. However, as this is not consistent with the results in Fig. 11(a), the effect of the residual FeO content is considered slight under the conditions changing sinter
properties in this work. On the other hand, in the softening under-load experiment presented in Fig. 6(b), the melting initiation temperature \( T_i \) shifted to the high temperature side as the \( \text{H}_2 \) concentration increased, and this is attributed to a decrease in the FeO concentration in the sinter accompanying the increased concentration of \( \text{H}_2 \), as hydrogen has a rapid reduction rate.

The dripping finish temperature \( T_f \), shown in Fig. 11(a) is lowest with sinter (D), which has a low slag fraction and viscosity. However, even though sinter (C) also has a low slag fraction, the \( T_f \) of sinter (C) is high. This is attributed to the fact that the basicity of sinter (C) is high, namely, \( \text{CaO}/\text{SiO}_2 = 2.48 \)--, and as a result, the viscosity of the dripping slag is also the highest.

4.4. Evaluation of Suitable Sinter Quality for Improvement of Gas Permeability in Blast Furnace

4.4.1. Outline of 2-Dimensional Model of Blast Furnace

Large operational changes occur in blast furnaces on a daily basis. In order to enable rapid prediction of the effects of charging conditions and blast conditions on blast furnace operation, JFE Steel Corporation developed a 2-dimensional model of the blast furnace.13,14 This model consists of a number of sub-models corresponding to various phenomena in the furnace, and makes it possible to obtain the 2-dimensional distribution of the furnace condition in the steady state by the calculation flow shown in Fig. 12.

In the model, the phenomenon of reduction degradation of sinter is treated as a decrease in mean particle size. The balance of the number of individual particles after degradation is obtained by combining this with the solid flow model shown in Fig. 12. The gas permeability in the lumpy zone and cohesive zone is calculated using the Ergun equation.31 The obtained particle diameter \( D_{po} \) of the sinter, which has a large effect on pressure drop in the furnace, can be obtained by Eq. (6), which is an equation3 proposed by Iwanaga.

\[
D_{po}=D_0-bf_s+a f_s^2 \tag{6}
\]

where, \( D_0, \) \( D_{po}, f_s, a, \) and \( b \) are \( D_0, \) \( D_{po}, \) initial and obtained particle size of sinter before and after reduction (mm), \( f_s: \) reduction rate (\%), and \( a, b: \) constants determined by the type and particle size of sinter and reduction temperature (\( °C \)), respectively.

In this research, the coefficient was obtained by regression assuming that the particle size of sinter can be expressed by Eq. (7), based on the results of the reduction degradation experiment in which the effect of the sinter properties and \( \text{H}_2 \) concentration were investigated.

\[
D_{po}=\gamma(D_0-bf_s+a f_s^2) \tag{7}
\]

where, \( \gamma \) is a constant (–). Eq. (7) is considered to be materialized in the range of mean \( \text{H}_2 \) concentrations in the reducing gas of 3.8–6.8 vol\%, which was used in these experiments. No large differences from this condition have been seen in blast furnace operation in recent years.

In the conventional model, pressure drop had been calculated assuming that the temperature in the cohesive zone is in the range of 1200–1400°C. However, based on the results in Fig. 11, the following regression equations were obtained for the melting initiation temperature \( T_i \) and the dripping finish temperature \( T_f \).

\[
T_i(°C)=1067.6+5.16-[\text{H}_2]+0.73 \cdot \text{RI}–0.64 \cdot \text{Slag}–10.8 \cdot \eta_{1500} \tag{8}
\]

\[
T_f(°C)=1452.6+0.026-[\text{H}_2]-4.35 \cdot \text{RI}+9.31 \cdot \text{Slag}+14.48 \cdot \eta_{1500} \tag{9}
\]

where, \([\text{H}_2]\), \( \text{RI} \), \( \text{Slag} \), and \( \eta_{1500} \) are \([\text{H}_2] \): hydrogen concentration in blast furnace at tuyere level (vol\%), \( \text{RI} \): reducibility index (%), \( \text{Slag} \): total percentage of slag (SiO\(_2+\)CaO+Al\(_2\)O\(_3+\)MgO) in sinter (wt\%), and \( \eta_{1500} \): viscosity of slag (Pa·s), respectively. In the model, the region defined by the temperature range from the melting initiation temperature \( T_i \) to the dripping finish temperature \( T_f \) is treated as the cohesive zone.

4.4.2. Evaluation of Sinter Quality by 2-Dimensional Model of Blast Furnace

Figure 13(a) shows the results of a calculation of pressure drop from the furnace top to the tuyere level, which was calculated using the 2-dimensional model of the blast furnace. The calculation conditions of the 2-dimensional model of the blast furnace were similar to those of actual blast furnaces in Japan, i.e., furnace volume: 5 500 m\(^3\), productivity: 2.2 t/m\(^3\)-d, RAR: 500 kg/t, and PCR: 160 kg/t. Sinter having the properties of sinter (A) was used in the calculation. The figure also shows the pressure drop obtained from the measured values of the shaft pressure gauges in an actual blast furnace. In the conventional 2-dimensional model of the blast furnace, the pressure drop from the furnace top to the tuyere level was smaller than that in actual blast furnaces. In particular, in the lumpy zone and cohesive zone, increasing deviation between the calculated and measured values of pressure drop was seen as the distance from the furnace top increased. On the other hand, no such deviations are seen in the results of the present analysis, and the calculated results are in good agreement with the pressure drop in the actual blast furnace. Therefore, the experimental heat patterns
were supposed to be valid in terms of introducing optimal regression equations for actual phenomena. In addition, Fig. 13(b) shows the shape of the cohesive zone as calculated using this model. In the conventional model, the cohesive zone was treated as the temperature region of 1200–1400°C; however, after the model was improved, the temperature range of the cohesive zone was 1140–1390°C. Thus, if the correspondence with pressure drop is considered, there is a possibility that the thickness of the cohesive zone was underestimated in the past results.

Next, Table 3 shows the results of an estimation of the effects of sinters (A)–(D) on gas permeability as calculated using this model. The calculation conditions for the burden were sinter rate: 63.2 wt%, lump ore ratio: 24.0 wt%, pellet ratio: 7.0 wt% and other iron sources: 5.8 wt%, and slag basicity was assumed to be constant. Fluctuations in productivity due to changes in TFe in the sinter were held constant by adjusting the blast rate.

As can be seen in the table, in operation using sinter (A), the pressure drop in the lumpy zone is high because the JIS-RDI of the sinter is high, and when using sinter (C), the pressure drop in the furnace bottom is high due to enlargement of the cohesive zone. Sinter (D), which has a low slag fraction and slag viscosity, is effective for improving the gas permeability in the blast furnace. Moreover, if it is possible to increase the RDI of sinter (D) up to the same level as sinter (C), these result showed that sinter (D) has the potential to enable an improvement of approximately 13% in gas permeability in comparison with use of sinter (A).

5. Conclusion

In this research, the blast furnace atmosphere in high PCR operation and operation with hydrogen-based reducing agents (LNG, H2) was reproduced, and the effects of sinter quality and reducing gas composition on the reduction degradation index (RDI) and softening under-load were investigated, focusing on pressure drop. Moreover, based on the results of these experiments, the accuracy of the conventional simulation model was improved, and the suitable sinter quality for improvement of gas permeability in the blast furnace was studied. The following results were obtained.

(1) In the reduction degradation experiment, reduction degradation of the sinter increased when the concentration of H2 in the reducing gas was increased. However, in the mean H2 concentration range of 3.8–6.8 vol%, the effect of H2 concentration on reduction degradation decreased. As the H2 concentration increased up to 3.8 vol%, diffusion of reducing gas to the interior of the sinter was promoted and the length of cracks increased. As a result, reduction degradation proceeded. On the other hand, in the H2 concen-
tration region over 3.8 vol%, diffusion became the rate-controlling step, therefore initiation and growth of cracks were retarded.

(2) High temperature properties, in other words, permeability could be improved by increasing the H₂ concentration or decreasing the amount of slag. Regarding the effect of the H₂ concentration, it is considered that formation of low melting point slag containing FeO could be depressed as a result of the increase in the reducibility by solids accompanying an increase in the reduction potential.

(3) The effects of sinter quality and reduction gas composition on RDI and softening under-load characteristics were formulated in an improved 2-dimensional blast furnace simulation model. The calculated value of pressure loss from the furnace top to the tuyere level with the new model showed closer agreement with the measured values from actual blast furnaces than those of the conventional model.

(4) Calculations using above-mentioned model showed that increasing RDI, the amount of slag and the viscosity of slag caused decreasing gas permeability in the blast furnace.

REFERENCES

26) M. Hoshi and T. Kawaguchi: CAMP-ISIJ, 12 (1999), 710.
30) M. Hoshi and T. Kawaguchi: CAMP-ISIJ, 12 (1999), 710.