Effect of Oxygen Enrichment on Sintering with Combined Usage of Coke Breeze and Gaseous Fuel

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The temperature in the sintering bed is preferably maintained between 1 200°C and 1 400°C during sintering to produce high strength and reducibility sintered ore. To achieve this condition, the technology of combined usage of coke breeze and gaseous fuel, which is fed properly from the top surface of the sintering bed, was developed. In this paper, the effect of oxygen enrichment with combined usage of coke breeze and gaseous fuel on the heat pattern in sintering bed and cold strength of sintered ore was investigated. The cold strength of sintered ore was improved by the oxygen enrichment in the pot test. Then, the holding time over 1 200°C during sintering was extended and improvement of strength would be attributed to promotion of the sintering reaction. By the simulation model calculations based on chemical kinetics, it is considered that the further extension of the holding time over 1 200°C due to oxygen enrichment is caused of an increase in the distance between the combustion points of the coke breeze and gaseous fuel. However, improvement of the cold strength reached saturation over 32 vol.% of the oxygen concentration in suction air. It is also considered that the excessive increase of the distance between the combustion points of coke breeze and gaseous fuel decreases overlap of respective heat transfer and doesn’t contribute to the expansion of holding time over 1 200°C.

KEY WORDS: sinter; gaseous fuel; oxygen enrichment; injection; heat pattern; combustion rate.

1. Introduction

In recent years, reduction of emissions of carbon dioxide (CO₂), which is a greenhouse effect gas, has become an important issue viewed in preservation of the global environment. In the ironmaking process, reduction of CO₂ emissions from coke and other carbon materials usage is demanded as a measure responding to this issue.

One of the policies to reduce CO₂ emissions in the ironmaking process is a reduction of the bonding agent in the iron ore sintering. The bonding agent ratio can be decreased by the improvement of product yield. For that, it is necessary to improve the cold strength of sintered ore.

In order to improve the strength of sintered ore, it is effective to increase the amount of melt that contributes to binding between ore particles.7) The initial melt forms and liquid phase sintering begins at around 1 200°C during temperature increasing in sintering bed. Therefore, the sintering bed should be held at a temperature over 1 200°C for a long time in order to achieve sufficient reaction and fusion of the raw materials. On the other hand, from the viewpoint of the reducibility of the sintered ore, it is required to hold the temperature of the sintering bed to less than 1 400°C, which is the thermal decomposition temperature of hematite, in order to prevent FeO formation. Accordingly, it is considered possible to achieve both high reducibility and high cold strength by holding the temperature between 1 200°C and 1 400°C, thereby suppressing formation of FeO while promoting liquid phase sintering.

In the previous paper,3) the authors reported the technology of combined usage of coke breeze and gaseous fuel, which is fed properly from the top surface of the sintering bed, to extend the holding time between 1 200°C to 1 400°C. Because the gaseous fuel started to burn at the upper side of the coke combustion zone, and the cooling rate of sinter decreased in the cooling state over 1 200°C.

To achieve a further advance in sintering technology, the effect of oxygen enrichment with combined usage of coke breeze and gaseous fuel was discussed in this paper. Studies on the usage of oxygen enrichment in sintering have been carried out by the authors, Sugawara et al.,4) Cappel et al.,5) Noda et al.6) and Kang et al.7) Although the influence for the combustion rate of solid fuel increasing has been discussed, the changes in the heat pattern with combustion in combined usage of coke breeze and gaseous fuel under an oxygen-enriched atmosphere was not understood enough. Then, it is important that the combustion behavior of gaseous fuel is different from that of solid fuel. Therefore, fundamental study was carried out at the laboratory scale, and the influence of oxygen enrichment on the heat pattern in sintering with combined usage of coke breeze and gaseous fuel was evaluated.
2. Experimental Method

In order to investigate changes in the heat pattern of oxygen enrichment with combined usage of coke breeze and gaseous fuel, the temperature measuring in the sintering bed was performed with sintering pot test. Figure 1 shows the experimental apparatus. In this experiment, the combustion behavior during sintering was observed directly by photography with a video camera in using a quartz glass pot (300 mm φ × 400 mm in height). The temperature distribution in the bed was also measured by infrared thermography. And Three R type thermocouples (1.6 mm φ × 200 mm in length) were inserted horizontally 150 mm into the sintering bed at vertical intervals of 100 mm from the top of surface in order to measure the temperature at the inside of the sintering bed. The holding time over 1 200°C at each measurement point was obtained from the results of the bed temperature measurements with these thermocouples.

Table 1 shows the blending ratio of the sintering mixture used in this experiment. And Table 2 shows the chemical compositions of Ore A and Ore B. Ore A is a dense ore produced in South America and Ore B is a porous ore produced in Australia.

The limestone, silica sand, return fine, and coke breeze were obtained by sampling at the commercial plant. In the predefined blending ratio of the materials, the return fine ratio was predefined at 20 mass%, and the blending ratio of the ores, limestone and silica sand were adjusted to obtain a SiO2 content of 4.8 mass% and basicity (CaO/SiO2) of 1.9 in the sinter. All of the raw materials were charged into a concrete mixer and mixed for 180 s at 20 rpm, after that the mixture was granulated for 360 s at 12 rpm by the 1 mφ drum mixer. The quasi-particles prepared in this manner were charged into the pot (approximately 42 kg/charge) and the hearth layer thickness was predefined at 20 mm. In the all cases, the suction pressure was constant at 6.9 kPa after ignition.

The gaseous fuel was gasified with liquefied natural gas (hereinafter, NG: CH4/C2H6/C3H8 = 89/5/6 vol.%). A nozzle was installed 400 mm above the surface of sintering bed in the hood. NG was injected for 6 min from 60 s after ignition, and the concentration of the NG in the suction air was controlled to the predefined value. Oxygen enrichment was performed in the same manner with pure oxygen as NG addition, through another nozzle in the hood. The oxygen concentration in the suction air from the above the pot was also controlled to the predefined value.

Table 3 shows the coke breeze, gaseous fuel, and oxygen enrichment conditions used in the sintering pot test. In this test, the suction air flow rate from the top of the test pot was measured using an orifice flow meter installed in the upper pipe of the hood at a position 100 mm from the nozzle, and the NG flow rate was adjusted so as to obtain the predefined NG concentration. From a previous paper, when the NG concentration exceeds the lean flammable limit (4.8 vol.%8)), it was found that the NG burned before arriving to the sintering bed; therefore, the NG concentration was predefined lower than the lean flammable limit. Furthermore, the NG concentration was predefined at 0.4 vol.% of the suction air because the improvement by NG addition reaches saturation if set at more than 10% of the lean flammable limit. The coke breeze blending ratio was predefined at 5.0 mass% of the total sintering mixture as a base condition. Under the condition of NG addition, coke breeze was reduced, equivalent to the added NG in combustion heat. Here, the combustion heat of coke breeze is higher heating value of 27.1 MJ/kg,9) assuming no generation of steam by reaction. The combustion heat of NG is lower heating value of 41.6 MJ/Nm3,10) assuming that combustion is accompanied by generation of steam and there is no condensation of steam at temperatures of 100°C or higher. The amount of coke breeze was not reduced in the case of oxygen enrichment, as oxygen does not have independent latent heat of combustion. The concentration of oxygen in the atmosphere (21 vol.%) was used as a standard condition, and under the condition of oxygen enrichment, the oxygen concentration in the suction gas was predefined at 28 vol.%. The oxygen flow rate was controlled to the predefined value corresponding to the flow rate shown by the orifice flow meter.

After the sintering pot test, the samples were dropped 1 time from a height of 2 m, and sinter with a size of 10 mm or larger was defined as product. Here, the sinter yield was calculated by the net weight of the sinter product divided by the total sinter cake. Sintering time was defined as the time

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**Table 1.** Blending ratio of sinter mixture used in the experiments. (mass%)

<table>
<thead>
<tr>
<th></th>
<th>Blending ore</th>
<th>Silica sand</th>
<th>Limestone</th>
<th>Return fine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore A</td>
<td>66.1</td>
<td>1.4</td>
<td>12.5</td>
<td>20.0</td>
</tr>
</tbody>
</table>

**Table 2.** Chemical composition of iron ores. (mass%)

<table>
<thead>
<tr>
<th>Material</th>
<th>TFe</th>
<th>FeO</th>
<th>SiO2</th>
<th>Al2O3</th>
<th>CaO</th>
<th>MgO</th>
<th>L.O.I.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore A</td>
<td>66.1</td>
<td>0.07</td>
<td>1.26</td>
<td>1.31</td>
<td>0.03</td>
<td>0.06</td>
<td>1.41</td>
</tr>
<tr>
<td>Ore B</td>
<td>58.1</td>
<td>0.36</td>
<td>5.39</td>
<td>1.43</td>
<td>0.33</td>
<td>0.13</td>
<td>10.40</td>
</tr>
</tbody>
</table>

**Table 3.** Experimental conditions in the sintering pot test.

<table>
<thead>
<tr>
<th></th>
<th>Case A</th>
<th>Case B</th>
<th>Case C</th>
<th>Case D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coke</td>
<td>5.0</td>
<td>4.6</td>
<td>5.0</td>
<td>4.6</td>
</tr>
<tr>
<td>NG</td>
<td>0.0</td>
<td>0.4</td>
<td>0.0</td>
<td>0.4</td>
</tr>
<tr>
<td>O2</td>
<td>21</td>
<td>21</td>
<td>28</td>
<td>28</td>
</tr>
</tbody>
</table>
from ignition until the exhaust gas reached its maximum temperature. The sinter production rate was calculated from the sinter product weight and the sintering time. The shatter index (SI) was measured according to JIS-M8711 (1993).

3. Experimental Results

3.1. Results of Heat Pattern Measurement

Figure 2 shows the observation results of the combustion behavior in the bed by the video camera and thermography. According to the results of video observation, in Case B, i.e., under sintering conditions using the coke breeze and NG without oxygen enrichment, the red-hot region expanded wider than the base condition using only coke breeze (Case A). On the other hand, in Case C, with oxygen enrichment using only coke breeze, the red-hot region did not expand wider than Case A. In Case D, with oxygen enrichment using coke breeze and NG, the red-hot region expanded to a greater degree than in Case A and Case B.

Similar tendencies could also be confirmed from the thermography images. Although the thermography images only showed the temperature condition in the vicinity of the side surface, a region over 1 400°C existed under the base condition in base Case A. But in Case B, a region over 1 400°C did not exist and the region over 1 200°C expanded wider than Case A. And moreover, in Case D, no region over 1 400°C was observed as in Case B, and the region over 1 200°C expanded wider than Case A and Case B.

Figure 3 shows the heat pattern as the results of temperature measurement at 100 mm from the top surface of sintering bed. Here, the x-axis shows the transit over time after ignition. After ignition, the sintering bed warms up to below 100°C with the formation of the moisture condensation zone. When the dry region with the progress downward of the carbon combustion passes through the measuring point, the temperature increases as large and rapid. The temperature has the maximum according to the balance of the heat quantity generated by carbon combustion and the cooling quantity by the downdraft suction air. After achieving this maximum, the temperature decreases by the cooling of the downdraft suction air.

In Case B, rapid temperature increasing began at substantially the same time as in the Case A. However, the holding time over 1 200°C was extended because cooling from the maximum temperature was more gradual. On the other hand, in Case C, the start of rapid temperature increasing occurred earlier and cooling from the maximum temperature was more rapid than Case A, resulting in a large decrease of holding time over 1 200°C. This is explained as follows: The combustion rate of the coke breeze was accelerated by oxygen enrichment, and the combustion of coke was finished in short time comparatively and reduced the width of the red-hot region. Therefore, pressure drop in this region decreased, and the ventilation airflow increased under a constant suction pressure condition.

In Case D, the start of rapid temperature increasing was earlier than Case A and Case B, and cooling from the maximum temperature was substantially the same as in Case B. Accordingly, in Case D the start of rapid temperature increasing was earlier and cooling from the maximum temperature was slower than Case A, and the holding time over 1 200°C was the longest among those conditions.

Figure 4 shows the holding time over 1 200°C measured by the thermocouples inserted at positions 100 mm, 200 mm,
and 300 mm from the bed surface. In the base Case A, the holding time over 1200°C increases as the depth in the sintering bed increases. Case C also shows the same tendency as Case A, and the holding time over 1200°C is shorter than Case A. On the other hand, in Case B, the holding time over 1200°C of the upper layer is 35 s longer, and that of the lower layer is 80 s shorter than Case A. In Case D, the tendency was similar to Case B, but the holding time over 1200°C at the position 100 mm from the bed surface is extended 65 s longer than Case A and 30 s longer than Case B. Thus, it was confirmed that the holding time over 1200°C in Case D was extended longer than Case B on the heat pattern.

3.2. Influence of Oxygen Enrichment on Sinter Quality and Sintering Properties

Figure 5 shows the sintering time under each experimental condition. In comparison with the base Case A, substantially no difference could be seen in the sintering time under Case B using the coke breeze and NG. In Case C with oxygen enrichment and using only coke breeze, the sintering time was greatly shortened. In Case D with oxygen enrichment and using coke breeze and NG, the sintering time was longer than Case C, but was shorter than Case A and Case B.

Next, Fig. 6 shows a comparison of the shatter strength and sinter yield under each condition. In Case B, both cold strength and sinter yield improved in comparison with the Case A. In Case C, cold strength was slightly higher than under the Case A, but sinter yield was unchanged. Furthermore, both cold strength and sinter yield in Case C was lower than Case B. In Case D, both cold strength and sinter yield were higher than in Case A and Case B.

3.3. Influence of Oxygen Concentration on Sinter Ore Quality and Sintering Properties

In order to investigate the effect of the oxygen concentration in Case D, an experiment was performed in which the oxygen concentration in the suction air was changed while holding the NG concentration constant at 0.4 vol.%. Figure 7 shows the relationship between the oxygen concentration and the shatter strength (SI) in Case D with oxygen enrichment and combined usage of coke breeze and NG. As the oxygen concentration was increased to 28 vol.%, SI also increased. However, when the oxygen concentration was increased to 32 vol.%, no large difference could be seen in comparison with the case of 28 vol.%. It is indicated that the effect of oxygen enrichment in improving SI had reached saturation. Figure 8 shows the relationship between the
oxygen concentration in the suction air and sintering time. As the oxygen concentration increased, sintering time became shorter.

4. Discussion

4.1. Influence of Oxygen Enrichment on Heat Pattern in Sintering with Combined Usage of Coke Breeze and NG

As shown in the section 3.1, based on the results of the heat pattern measurements, in Case B, using coke breeze and NG without oxygen enrichment, the holding time over 1200°C was extended longer than the base Case A, and it was explained by the result of more gradual cooling from the maximum temperature. As also shown in a previous paper, it is considered that cooling was more gradual than in the base Case A because the NG added from the top of the sintering bed began to burn above the coke breeze combustion zone, and the resulting heated gas was then sucked downward into the red-hot region. Here, it should be noted that the combustion temperature range of methane gas in the concentration range 2 to 12 vol.% with a vacuum, which comprises approximately 90% of the NG, is 650 to 750°C.11)

Although the blending ratio of coke breeze was the same in both cases, with oxygen enrichment but using only coke breeze in Case C, the starting time of rapid temperature increasing was earlier than under the base Case A. Cooling from the maximum temperature was rapid, and the maximum temperature was also higher. This is estimated to be due to the increase in the combustion rate of the coke breeze by the elevated oxygen concentration.

The general reaction rate equation for the combustion reaction of carbon (C) in coke breeze, namely, C(s) + O2(g) = CO2(g), can be expressed by the following equation, assuming the rate of the reverse reaction is ignored: 12,13)

\[ R_c^* = n_C \cdot 4\pi r^2 k_c [O_2] \] .......... (1)

- \( R_c^* \): reaction rate (mol/s)
- \( n_C \): reaction rate constant (m/s)
- \( r \): radius of carbon particle (m)
- \([O_2]\): oxygen concentration (mol/m³)

Here, the combustion rate of carbon increases in proportion to the oxygen concentration in the suction air. The reaction rate constant is influenced by temperature, and becomes larger as temperature increases.15) Hottel et al. measured the combustion rate of single sphere particles of carbon and reported the rate constant[15-17] and the rate constant was ordered as the following equation by Muchi et al.18)

\[ k_c = 6.53 \times 10^9 \exp \left( \frac{-44000}{RT} \right) \sqrt{T} \] .......... (2)

- \( R \): gas constant (cal/K/mol)
- \( T \): temperature (K)

As the combustion temperature of carbon is approximately 800°C, relationship between the temperature near 800°C and the combustion rate per unit of area obtained from Eqs. (1) and (2) is as shown in Fig. 9. At an oxygen concentration of 21 vol.%, the combustion rate per unit of area at 800°C is 47 mol/s/m², and increases to 56 mol/s/m² at 25 vol.% and 65 mol/s/m² at 29 vol.%. On the other hand, each combustion rate is equivalent in the conditions of temperature of 800°C at an oxygen concentration of 21 vol.%, 790°C at 25 vol.% and 780°C at 29 vol.%.

Accordingly, because combustion of carbon progresses from a low temperature and the combustion rate is increased with increasing the oxygen concentration, it is considered that oxygen enrichment results in an earlier start of the rapid temperature increase in the heat pattern.

NG comprises approximately 90% methane (CH4). The general combustion reaction rate equation for hydrocarbons is expressed by a combination of many elementary reactions. For example, in the methane combustion reaction (CH4(g) + 2O2(g) = CO2(g) + 2H2O(g)), CH4 changes through some intermediate products; CH3, CH2O, HCO, CO, H2 etc. to CO2 and H2O.19) Here, the combustion rate of methane gas expressed by a following equation.11)

\[ R_{CH4}^* = k_{CH4}[CH_4]^i[CH_3]^j[CH_2O]^k[CO]^l[H_2]^m \cdots [O_2]^x \] .......... (3)

- \( R_{CH4}^* \): reaction rate (mol/s/m²)
- \( k_{CH4} \): reaction rate constant (m/s)
- \([i]^j \): concentration of element i (mol/m³)
- \([O_2]\): concentration of oxygen (mol/m³)
- \( i, X \): order in reaction equation (-)

At this time, the reaction rate constant \( k_{CH4} \) is expressed by \( k = A \exp(-E/RT) \), arranged in accordance with the Arrhenius equation. It is a function of temperature. Furthermore, in Eq. (3), the combustion rate increases with increasing oxygen concentration in the same manner as the combustion rate of carbon.

Figure 10 shows a schematic diagram of the relationship between the heat pattern and the combustion positions of the solid bonding agent (coke) and NG in the vertical direction for all Cases, assuming the same elapsed time after ignition. In Case A, coke combustion occurs within a comparatively narrow range in the vertical direction and forms the heat pattern shown by (a) in the figure. On the other hand, in Case B, the NG burns in the upper part of the coke combustion position and the sinter is cooled more slowly above the coke combustion position because the heated gas by NG combustion supplies to the cooling region. Therefore, the heat pattern shown by (b) is formed. In Case C, because the combustion rate and heat generation rate of coke breeze is increased by...
the increased oxygen concentration, heat transfer by convection to the lower part materials is increased through the downdraft gas flow. And then, the coke combustion position advances in the lower part of the bed at an earlier time. As a result, the heat pattern of Case C shifts to lower direction than the heat pattern of Case A as shown by (c) in the figure. In case D, the coke combustion position advances in the lower part of the bed by oxygen enrichment too. On the other hand, the increased oxygen concentration also increases the combustion rate of NG, and combustion of NG added from the surface of the sintering bed occurs on the low temperature side in the upper part of the bed. As a result, it is considered that Case D forms a heat pattern with an expanded high temperature region over 1200°C in comparison with Case B, as shown by (d) in the figure, by further expanding the distance between the combustion positions of the coke and NG in comparison with Case B.

4.2. Studies by Simulation Model

The influence of the various conditions on the heat pattern was confirmed by using a numerical simulation model that considered combustion of methane. In this simulation model, the basic state was prescribed with differential equations based on the conservation laws of mass, enthalpy and momentum. The combustion of coke breeze, decomposition of CaCO₃, evaporation-condensation of water were considered as the main reactions during sintering. Moreover, the combustion rate of CH₄ gas was installed into the mathematical model to calculate the temperature distribution with the gaseous fuel injection method. Oxygen and CH₄ addition was carried out by the control of the gas composition at the boundary.

First, the heat patterns obtained with the simulation model and laboratory sintering pot tests were compared. In Case B with combined usage of coke breeze and NG without oxygen enrichment, as shown in Table 3, the calculation conditions were given as the coke breeze blending ratio was predefined at 4.6 mass% and the NG concentration was predefined at 0.4 vol.% in the suction air, and NG was added immediately after the point of ignition for 6 min.. In Case C with oxygen

Fig. 10. Schematic diagram of heat pattern and ignition behavior with Case A, B, D.

Fig. 11. Comparison of heat patterns between experimental value and calculated one at 100 mm from the top surface of sintering bed.

Fig. 12. Effect of the O₂ concentration on the temperature distribution in the Case D with the simulation model at 200 s after ignition.
enrichment using only coke breeze, the calculation conditions were given as the coke breeze blending ratio was predefined at 5.0 mass\%, and the oxygen concentration was predefined at 28 vol.\% in suction air. Figure 11 shows the experimental results and calculated results for the heat pattern at 100 mm below the top of sintering bed surface. In both Case B and Case C, the calculated results were close to the experimental results in the temperature region over 800°\C. From this, it was inferred that the reason of heat pattern changes in the temperature region over 1200°\C was also possible understood using this model.

Here, the influence of the oxygen concentration was studied in Case D, as oxygen enrichment with using coke breeze and NG. Figure 12 shows the calculated heat patterns of the three oxygen concentrations at 200 s after ignition with the constant methane concentration of 0.4 vol.\%. The calculation range was set to a depth of 100 mm downward from the top of surface. In this calculation, NG and oxygen was added with the injection timing as previously indicated for Fig. 11. In the calculation results, as the oxygen concentration was increased from 21% to 28% and then 36%, the position where the coke breeze combustion rate was maximum shifted downward in steps of approximately 5 mm, and the maximum combustion rate also became higher in steps of approximately 40 mol/Bed-m\(^3\)/s. In the following, this position is called to the combustion point. Therefore, the combustion point was considered to advances downward more rapidly by the increase in the combustion rate of coke breeze.

Although the oxygen concentration increased, the combustion point of methane did not change. Figure 13 shows schematic diagram of heat pattern change with oxygen enrichment in the simulation model. The heat pattern and combustion point of CH\(_4\) shift to lower direction by the shift of coke breeze combustion point as shown by (a) in Fig. 13. On the other had, the temperature getting the equivalent combustion rate decreases with increases in oxygen concentration as discussed in section 4.1, and the CH\(_4\) combustion point shift to upper direction, in which temperature is low as shown by (b) in Fig. 13. Therefore, the shift of coke breeze combustion point offset the shift of CH\(_4\) combustion point and the shift of CH\(_4\) combustion point is smaller than coke breeze.

As the result, the distance between the combustion points of coke breeze and methane became larger with the increase in the oxygen concentration. And the heat pattern changed as shown in Fig. 12. Specifically, when the oxygen concentration was increased from 21\% to 28\%, the region over 1200°C expanded from 25 mm to 35 mm. However, when the oxygen concentration was increased to 36 vol.\%, the region over 1200°C remained at 35 mm. The effect of oxygen enrichment in expanding the region over 1200°C reached saturation at an oxygen concentration of 36 vol.\% because the distance between the combustion points of the coke breeze and methane became excessively large, and as a result, combustion of methane no longer had the effect for to moderating the cooling rate in the cooling region after completion of coke breeze combustion.

4.3. Influence of Oxygen Enrichment on Sintering Properties

As shown in Fig. 4, in the sintering test under a constant suction pressure condition, the sintering time decreased substantially in Case C, as oxygen enrichment using only coke breeze. As discussed above, this was estimated due to the increase of combustion rate by oxygen enrichment. On the other hand, in Case D, as oxygen enrichment with using of coke breeze and NG, the sintering time was longer than Case C, and was shorter than Case B. On the extension of the sintering time in Case D in comparison with Case C, the reason was estimated that pressure drop increased due to expansion of the high temperature region by simultaneous addition of NG and oxygen. Figure 14 shows the calculated results of the temperature distribution and pressure distribution in the bed in Cases C and D at 250 s after ignition when the bed height was 400 mm and the gas flow rate was predefined constantly at 0.6 N m\(^3\)/s. The high temperature region over 1200°C in Case D has expanded from 15 mm to 35 mm, while the pressure drop in the this region increased from 0.12 kPa in Case C to 0.33 kPa in Case D. The pressure drop in the total bed was 2.06 kPa in Case C and 2.23 kPa in Case D. Therefore, the difference in the pressure drop of the total bed was due to the difference of the pressure drop in the high temperature region. On the other hand, under the condition of a constant suction air flow rate, there was little difference in the position of rapid temperature increase. Hereinafter the position of rapid temperature increase is called to the Flame Front: FF. Then, because the concentration of added NG was extremely small as 0.4 vol.\%, the oxygen concentration feeding to the coke combustion region after combustion of NG was decreased still slightly on the order of 0.8 vol.\%. Accordingly, it was supposed that a large dif-

![Fig. 13. Schematic diagram of heat pattern change with O\(_2\) enrichment in the simulation model.](image-url)
ference in combustibility of coke breeze did not appear and a large difference in FF was not apparent. The main cause of the longer sintering time in Case D than in Case C was considered to be the increase in pressure drop due to expansion of the high temperature region.

As the reason why the sintering time was shorter in Case D than Case B, though the high temperature region over 1200°C was expanded in Case D than in Case B, it was estimated that the effect by increasing combustibility of coke breeze due to oxygen enrichment was larger than the effect of the increase in pressure drop due to expansion of the high temperature region. Figure 15 shows the calculation results of the temperature distribution and pressure distribution in the bed for Case B and D with the calculation condition as previously indicated for Fig. 14. The high temperature region over 1200°C has expanded from 25 mm to 35 mm in Case D, and pressure drop increased to 0.23 kPa in Case C and 0.33 kPa in Case D. Moreover, in Case D, the speed of the FF moving downward, this speed is called to the FFS, showed a remarkable increase accompanied by the increased combustibility due to oxygen enrichment, FF has advanced 15 mm further downward in Case D than in Case B. Therefore, the main cause of the higher FFS and the short sintering time in Case D than in Case B under the constant suction pressure was considered that the increased combustibility of the coke breeze due to oxygen enrichment had a large effect, even considering the influence of pressure drop.

Regarding shatter strength and sinter yield in Fig. 6, both values were higher in Case B than the base Case A, and also showed higher values in Case D than Case B. As shown in Fig. 4, this was estimated to be due to extension of the holding time over 1200°C in the upper side of the bed, which was 160 s in the base Case A, 195 s in Case B, and 225 s in Case D. In the sintering reaction, the melt begins to generate over 1200°C. This means that the holding time over 1200°C is the substantial sintering reaction time. Therefore, shatter strength and productivity were estimated to improve in Case D because the sintering reaction progressed in comparison with Case B. On the other hand, in Case C, the holding time was shorter than Case B as shown in Fig. 6. As the holding time over 1200°C at the thermocouples 100 mm and 200 mm below the top of the surface also decreased 110 s and 175 s, this was attributed to the shorter sintering reaction time. Although the holding time over 1200°C in Case C was shorter than the base Case A, as in the experimental results reported by Ishimitsu et al., no changes were observed in shatter strength and productivity.

Figure 16 shows the relationship between productivity and shatter strength under the each experimental condition of the sintering pot tests. Here, the productivity was calculated by the net weight of the sinter product divided by the section area of the test pot and sintering time. In comparison between Case D and Case B, the high temperature holding time was extended and the sintering time was shortened in Case D, and as a result, productivity and shatter strength improved. On the other hand, in comparison between Case D and Case C, because the high temperature holding time was greatly extended in Case D, shatter strength also improved. Although the sintering time extended slightly, productivity improved due to the improved yield associated with higher shatter strength. And shatter strength and productivity improved in Case D compared with the summation of each effect in Cases B and C due to a so-called synergistic effect by simultaneous usage of NG and oxygen.

5. Conclusion

(1) The cold strength of sintered ore was substantially improved by the oxygen enrichment with combined usage of coke breeze and gaseous fuel. This improvement was attributed to extension of the holding time over 1200°C during sintering and promotion of the sintering reaction.

(2) The extension of the holding time was considered to be a result of an increase in the distance between the combustion points of the coke breeze and gaseous fuel with higher oxygen concentrations.

(3) In the case of sintering with oxygen enrichment and using coke breeze and 0.4 vol.% natural gas as NG, the effect of oxygen enrichment in improving the shatter index as SI reached saturation when the oxygen concentration was increased to 32 vol.%. It is thought that NG combustion no longer contributed to expansion of the region over 1200°C because the distance between the combustion points of the coke breeze and NG became excessively large.

(4) The shatter strength and productivity more improved in the oxygen enrichment with combined usage of coke breeze and gaseous fuel comparing with simple sum of each effect in gaseous fuel addition and oxygen enrichment due to a synergistic effect by simultaneous usage of NG and oxygen as discussed before.
REFERENCES

16) H. Davis and H. C. Hottel: ibid., 26 (1934), 889.
17) A. Parker and H. C. Hottel: ibid., 28 (1936), 1334.