Influence of Oxygen Supply in an Iron Ore Sintering Process

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The current issues of sintering technology in the iron and steel making industry are how to increase productivity of sintering process and to maintain proper quality of sintered ore. In the conventional sintering bed, combustion of solid fuel supplies heat required for sintering while it generates imbalance of heat concentration in the bed. The unevenly distributed heat is considered to be problematic on the quality aspect of sintered ore. Therefore, in order to maximize the production rate and quality of the products, an investigation for improved operational mode is indispensable. In this study, the effect of additional oxygen supply with an adjustment of injection location is discussed. Scale downed pot tests in addition to computation by previously developed unsteady 1-dimensional sintering bed model are employed for the examination. Also, quantitative parameters are applied to evaluate the changes of sintering process and the combustion characteristics are systematically analyzed among designed cases. The reactivity of coke combustion tends to increase with the enrichment of oxygen in the induced air. However, the degree of change in the sintering time as well as effective heat supply varies according to the locations of oxygen injection.

KEY WORDS: iron ore sintering bed; oxygen enrichment; coke combustion.

1. Introduction

Sintering is technology for agglomeration of iron ore fines into useful blast furnace burden material. In the iron ore sintering process, a raw mix of fine particles of iron ore, limestone and fuel coke fines form pseudo particles after being mixed with water. These pseudo particles are then fed to the traveling grate to form a bed. After the feed material is introduced to the bed, combustion starts from the top of the bed by the ignition burner and air is supplied through a down draft suction fan. Then, the combustion front propagates downward and process of sintering commences where the temperature of combustion zone is high enough. Below the combustion front, the combustion gas evaporates moisture in the solid particles, while condensation occurs below the evaporation zone. These processes progress slowly through a traveling bed of some 100 m length.

Figure 1 shows imbalance of heat distribution, and unevenly distributed heat is considered to be problematic on the quality aspects of sintered ores. In the sintering process, productivity is determined by vertical fuel combustion speed or elapsed time for the complete combustion of coke in the bed. The quality indices are composite of strength and FeO content of the sintered ore.

In order to maximize the productivity and quality of the products, various ideas have been proposed. There were several approaches to boost efficiency of the sintering process, which include double ignition, heat supply from alternative fuel, different granulation of pseudo particle, change of inlet gas composition and so on.

Among diverse methods, variation of inlet gas condition is considered to be one of the most practical solutions without fully retrofitting the existing plant for the better utilization of coke combustion with adequate heat supply. Figure 2 and Table 1 show the expected effect from the inlet gas variation method. Productivity, quality, energy use and investment cost differences are comparatively evaluated base on the different composition of inlet gas supply. Conventional operation system is set to be the reference and each method is conceptually estimated.

In this study, the effect of additional oxygen supply with an adjustment of injection location is investigated through experimental and numerical approach. To evaluate the change of sintering process, quantitative parameters are applied to the calculation results, and the combustion char-

Fig. 1. Conceptual diagram of the sintering process.
acteristic are analyzed in terms of proper heat supply with completion time of sintering process.

2. Sintering Pot Test

2.1. Test Apparatus

Figure 3 shows a schematic diagram of the sintering test rig. The bed has a diameter of 150 mm and a height of 400 mm. R-type thermocouples are installed along the axial direction of the bed and each location represents upper (y=300 mm), middle (y=200 mm), lower (100 mm) area of the sintered ore. Also, K-type thermocouple is installed in the wind box to check the waste gas temperature. At the bottom of the bed, previously sintered particles of 8–10 mm in diameter are placed to provide permeable condition for bed combustion during the process.

For the variation of inlet gas condition, gas mixer is attached to blend oxygen with additional gas supply. The progress of sintering is monitored with the downstream gas analyzer and the volumetric gas flow rate at the outlet of the bed is constantly checked. In addition to the pot made of steel, transparent hard glass pot is prepared. To visually record propagation pattern of the combustion, CCD camera is placed 0.5 m away from the sintering pot.

2.2. Sintering

A raw mix of iron ores, limestone, and fuel coke fines was sampled from the rerolling drum of actual sintering plant. Table 2 shows typical composition of solid materials in an iron ore sintering bed. Those fine particles of iron ore and other additives had been mixed with water. For every single test, 13 kg of granules with 400 g of hearth ore are fed to the pot. After the preparation of the raw materials, the bed is exposed to the LPG burner for 60 s thereby begins to ignite. The pressure difference of the suction fan is set at 1 000 mmAq during the ignition period and increases to the 1 500 mmAq afterward. Figure 4 shows typical profiles of the pressure difference and gas flow rate measured during the air supplied reference case. After the initial value is set, the suction pressure varies as coke combustion progresses while the rotation speed of the fan is kept constant.

After ignition, the LPG/air flow is stopped. The burner is quickly lifted off from the pot. Then the ambient air is induced through the ignited material and the flame front propagates throughout the raw material region. As the combustion zone moves downward, the bed temperature significantly increases. The gas outlet temperature is monitored and it slightly rises during the process.

When cooled, the sinter cake is removed from the pot and examined its degree of sintering as shown in Fig. 5. In the upper region of sintered cake, some raw materials are not

1. Normal operation—Reference.
2. O2 enriched operation.
3. LNG supplied operation.
4. O2 and LNG combined operation. +: degree of increase; •: None
fully combusted due to the low maximum temperature and short high temperature holding time. On the other hand, heat accumulated in the bottom of the bed generates excessive quality of sintered ore.

2.3. Case Setup

In order to observe the effect of oxygen supply with an injection location, several test cases are selected. Two parameters including oxygen concentration in the inlet gas and the location of additional oxygen supply are mainly concerned.

For comparison, air operation case is set as reference and 65 liter/min (average) of additional oxygen is supplied to the other cases. It should be noted that the time consumed for injection of additional oxygen supply for each cases are not identical. It can be varied from 80 s to 100 s as the flow rate slightly increases due to the combustion propagation. Table 3 shows the injection time and locations of oxygen concentration of each case.

<table>
<thead>
<tr>
<th>Case Name</th>
<th>Oxygen (%)</th>
<th>Injection Location</th>
<th>Injection Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>21</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>U30</td>
<td>30</td>
<td>Upper</td>
<td>295–395</td>
</tr>
<tr>
<td>M30</td>
<td>30</td>
<td>Middle</td>
<td>479–574</td>
</tr>
<tr>
<td>L30</td>
<td>30</td>
<td>Lower</td>
<td>665–745</td>
</tr>
</tbody>
</table>

2.4. Experimental Results and Discussion

Figure 7 shows the temperature variation of selected locations for oxygen injection cases. In the case of oxygen upper injection (U30), the temperature slightly increases after additional oxygen is supplied. The similar pattern is repeated in the middle injection (M30) as well. The reactivity of coke combustion significantly increases with the enrichment of oxygen in the induced air. From the temperature distribution of both cases, effect of oxygen supply on bed temperature rise can be identified. It might not be the linear relationship between the rise of coke combustion rate and additional oxygen supply. However, it can be assumed that the temperature increase is proportional to the degree of oxygen enrichment until it reaches a certain value where the oxygen enrichment is influential.

As shown in Fig. 8, temperature zone which is high enough to either combust or melt the solid materials in the bed can be visually observed through the hard glass pot test. Typically, the thickness of high temperature zone tends to be widened as the combustion front goes downward. It is because the temperature of air supplied to the subjected region slightly increases due to the convection heat transfer from heated particles, and the combustion rate also increase as solid temperature rises at the lower part of bed.

In the test results, higher temperature zone expands with combustion propagation as usual. However, the brightness is comparatively improved and the degree of combustion zone...
thickness is significantly increased. Accelerated coke combustion leads the flame front speed to rise and it attributes to the increment of combustion zone thickness with higher temperature than usual while the additional oxygen is supplied. However, those phenomena steadily disappear when it turns to the normal operation.

### 3. Application of Numerical Model

#### 3.1. Model Description

Numerical model of iron ore sintering process is adopted from the previous study. In the mathematical model, the sintering bed is assumed as a homogeneous continuum of solid and gas phases. Solid material is treated as multiple solid phases, which makes it possible to consider different fuel characteristics. For a 1-dimensional system of the y-coordinate, the governing equation can be represented as a form of partial differential equation, which is shown as,

\[
\frac{\partial (\rho f \phi)}{\partial t} + \frac{\partial (\rho f v)}{\partial y} = \nabla \cdot \left( \Gamma_{\phi} \nabla \phi \right) + S_{\phi} \quad \text{(1)}
\]

Mass, energy, component and chemical species conservation equation for each phase are constructed and several sub models are combined to supplement each terms of governing equations and those equations interact with chemical reactions, various modes of heat transfer and geometrical changes of the solid particles. General description of sub model is shown in Table 4 and details are represented in the previous research.

#### 3.2. Quantitative Parameters

To adequately evaluate the sintering process, characterization of bed combustion is required. In this study, sintering time (ST), combustion zone thickness (CZT), melting zone thickness (MZT) and maximum temperature (MaxT) are employed for the interpretation of simulation results. ST is defined as the elapsed time until the flue gas temperature indicates a maximum, and it is used to express the combustion propagation speed. While the ST serves as the index for the productivity of the sintering process, CZT and MZT as well as MaxT are adopted to properly predict the quality of sintered ore. These parameters are determined from the computational model. CZT and MZT are defined as the thickness of combustion zone and melting zone which are set to be above certain temperature. Adding to that, the maximum temperature is defined as the highest temperature of the solid materials at a given time. The detailed information of these parameters is described in Table 5.

#### 3.3. Simulation Results and Discussion

Simulation cases are designed to match the experiment, in which oxygen concentration and the location of additional gas injection are mainly changed. The specified operating conditions are described in Table 3.

Figure 9(a) shows the simulation result of the temperature distribution within the bed where the induced gas is set as air. The combustion is sustained by coke reaction once
Ignited. Compare to the reference, overall temperature profile with oxygen supply is shown in Fig. 9(b). When the 30% of oxygen in the inlet gas is supplied at the subjected region, the temperature pattern is significantly changed. Additional oxygen prompts coke combustion rate to be increased and the bed temperature rapidly rises as the consequence. The higher temperature region including combustion zone and melting zone tend to move downward rapidly with oxygen enrichment. Those phenomena do not simply disappear even though the operation parameter returns to the normal condition where the induced gas in the sintering bed is air. It is because the effect of additional oxygen supply still remains due to the increased solid phase temperature. Though the oxygen concentration in the inlet gas returns to the 21%, extended higher temperature zone still influence the coke combustion rate and its phenomena lasts for certain period of time. However, with the continuing convection cooling from the induced air, those trends begin to subside and the temperature pattern, varied from oxygen supply, returns to the similar condition of normal operation.

Figure 10 shows temperature distribution at the specified point. In here, temperature at \( y=200 \) is simulated, and the difference resulted from varying oxygen concentration is clearly shown in terms of temperature increment rate. Compared to the oxygen middle and lower injection, temperature increment pattern of upper cases appeared in advance. Those trends are repeatedly shown in the other points with the variation of oxygen contents in the air. In other words, if the additional oxygen is supplied at the upper, middle and lower region in the bed, following area of combustion zone rapidly moves toward the bottom of the bed until the oxygen effect is influential.

Figure 11 shows the sintering time of various cases. This parameter is defined as the completion of sintering process in which the flue gas temperature reaches maximum. As additional oxygen supply is made based on the variation of injection location, its values slightly differs at least few seconds to 50 seconds at most. The difference shown among those cases is attributed to the moisture contents in the solid phase. To form a bed, raw materials including coke, iron ore, limestone are mixed with water. Therefore certain amount of water exists in the sintering bed. After the ignition, inlet gas passes through the cooling zone, combustion zone and raw material zone respectively. As the combustion progresses downward, raw material zone is getting reduced thereby decreasing heat loss from evaporation of moisture contents. As mentioned previously, the fuel combustion rate increases while additional oxygen is supplied. However it also shows that the trend influenced by oxygen enrichment doesn’t last continually, but tends to subside when it turns to the normal operation. Therefore, the sintering time is shortened as the injection location is lowered along the bed height. But this quantified parameter needs to be evaluated more carefully. Actual bed flow rate with oxygen enrichment would be slightly different since the melting fraction of raw material varies with different inlet gas condition.

Figure 12 represents the mass decrease rate of various cases. As shown in the picture, carbon content of coke in the sintering bed gradually decreases while the solid fuel combustion continues. Mass decrease rate changes as a result of variation of oxygen concentration in the inlet gas. In here, the differences of those rates are not only affected by oxygen contents, but also the injection location. Furthermore, the degrees of change on the mass decrease rates are slightly different. It tends to increase as the location of oxygen injection is lowered. In other words, mass decrease rate at the lower part of bed is more significant. It is because the combustion zone is wider and the maximum temperature is
Higher than that of upper and middle part of bed in the typical operation. Increased solid phase temperature provides favorable condition for coke combustion thereby raising reaction rate which can be represented by mass decrease rate. However, injecting additional oxygen at the lower part of bed should be carefully discussed, because excessive heat is already accumulated in this area.

**Figure 13** shows combustion propagation tendency inside the sintering bed and heat balance terms are represented by solid-gas convection, radiation, conduction as well as solid-gas reaction. These values are compared at the location of y=300 mm, 100 mm. (upper and lower part of bed respectively). As shown in the figure, solid gas convection is the dominant mode of heat transfer in the initial stage. Drying and heating of solid particles are initiated through the convection, and then coke combustion commence when the temperature of solid particles is increased. The degree of change for the radiation and conduction is relatively lower than coke combustion. Here, it is found that the additional oxygen supply significantly affects the char combustion rate. Compare to the normal case, the heat generated by char combustion is not only increased, but also quickened, implying that the rate of coke combustion is gradually increased in the projected region.

The other important quantitative parameters are maximum temperature (Max.T), combustion zone thickness (CZT) and melting zone thickness (MZT), and the results are shown in **Figs. 14** and **15** respectively. For investigating combustion condition in the solid bed, the temperature is considered to be one of the most important parameters. Especially in iron ore sintering bed, the maximum temperature and the thickness of combustion zone and melting zone should be carefully discussed because there is melted iron ore fraction among solid materials and it significantly affects the bed permeability. The maximum temperature is defined as the mean temperature of the solid material at given time. It indicates the amount of heat and the degree of heat concentration in the bed. As shown in Fig. 14, the maximum temperature gradually increases in the normal operation. When the additional oxygen is supplied, its values slightly increase during the projected time frame. Those phenomena repeatedly appear as the injection location varies. With the enrichment of oxygen supply in the subjected region, reaction heat of coke combustion concentrates at the corresponding area. Also, the combustion zone thickness and melting zone thickness show different values since the temperature inside the sintering bed changes. Those parameters are fluctuating according to the oxygen supply with variation of location. The degree of melting zone thickness varies faster than combustion zone thickness while the additional oxygen is supplied. It means combustion front moves faster than normal operation. From the simulation results, expansions of melting zone from various oxygen supply cases are predicted. Those patterns affect the bed condition in terms of combustion condition and quality of the sintered ore. Therefore, its influence should be further discussed.

**Figure 16** shows the maximum temperature of the bed with the variation of oxygen concentration where 25% and 30% of oxygen in the induced air are reflected. As the concentration of oxygen is reduced, the maximum temperature slightly decreases. The difference between the temperatures of two cases is not significant. But, at the given time, the rate of increasing tendency of the maximum temperature is higher for the case of 30% oxygen concentration than 25%. It means more oxygen concentration, faster combustion rate. The combustion zone thickness, melting zone thickness tends to decrease with the reduction of oxygen contents in the induced air. These results correspond to the maximum temperature profile of 25%, 30% of oxygen supply. Select-
ing proper amount of oxygen is one of the important factors in addition to an adjustment of oxygen supply location since it significantly influences the quality of sintered ore. Maximum temperature and combustion thickness are affected by change of oxygen concentration. Therefore, operating parameter related to these characteristics should be determined carefully for optimization of the operating conditions.

4. Conclusion

The aim of this work was to systemically analyze the effectiveness of alternative operating conditions of sintering process, especially oxygen enrichment at the selective region of the sintering bed. In this study, effect of oxygen supply with an adjustment of injection location is investigated through sintering pot test. Temperature, flow rate and combustion zone trend are attained and the change of these pattern from oxygen injection is discussed. Also, previously developed numerical model is adopted to gain more detailed information of combustion phenomena inside the bed. Temperature distribution, flame front speed and sintering time which represents propagation speed of the combustion zone are employed for quantification of the simulation cases.

From the results, it is found that the enrichment of oxygen concentration in the induced air provides effective heat utilization required for the sintering bed such as fast coke fuel combustion and high temperature at the subjected area. To maintain proper strength of sintered ores, high temperature should be maintained especially in the upper part of the bed. The insufficient heat at the upper area is considered to be the problem, thus supplying oxygen into the projected region can bring better quality of sintered ore.

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REFERENCES