Development of Temperature Control Technology by Gaseous Fuel and Oxygen in Iron Ore Sintering Process

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Abstract:

Reduction of CO₂ emissions has become an urgent issue as represented by the SDGs in recent years, and at the same time, the iron and steel industry is also strongly required to reduce CO_2 emissions from the ironmaking process. In JFE Steel, the gaseous fuel injection technology (Super-SINTERTM) was developed and installed to actual sintering machine in 2009. In this technology, the predetermined amount of hydrocarbon gaseous fuel injection from bed surface extended holding time over 1 200°C at which liquid phase sintering occurs. This technology was applied to a plant, and by the reduction of coke usage in sintering and blast furnace process, a maximum CO₂ reduction of 60 000 t/y was achieved. Moreover, by controlling combustion rate of coke and gaseous fuel with gaseous fuel and oxygen injection technology (Super-SINTERTM OXY), improvement of further extension of holding time over 1 200°C was successfully achieved.

1. Introduction

In recent years, the development of technologies for CO_2 emission reduction as a countermeasure for climate change has become an urgent challenge. Since the sintering and blast furnace processes generate about 60 % of more of total CO_2 emissions in the iron and steel industry¹, reduction of use of coke breeze in sintering machines and lump coke in blast furnaces has been strongly demanded. It is generally known that improvement of the strength and reducibility of sinter is effective for reducing the coke breeze ratio and lump coke ratio². In the sintering process, raw materials

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¹ Senior Researcher Deputy Manager, Ironmaking Research Dept., Steel Res. Lab., JFE Steel begin melting from approximately 1 200°C, and agglomeration proceeds by penetration and solidification of the formed melt between ore. A high strength calcium-ferrite texture³⁾ forms from this melt, but this texture decomposes at around 1 400°C. Therefore, controlling the reaction temperature between 1 200 to 1 400°C is effective for producing high strength sinter.

Until now, several technologies for increasing strength without increasing the coke breeze ratio have been proposed. For example, a circulation system for the exhaust gas of the sintering machine and use of its sensible heat to reduce the cooling rate has been reported⁴, but on the other hand, it was also reported that productivity will decrease if the recirculated exhaust gas has a low O_2 concentration and high moisture content⁵. A preheated air injection method was also proposed⁶, but the application of that technique is reportedly limited, as the preheated air does not affect combustion of coke breeze⁷. For these reasons, there are limits to the application of each of these techniques to the sintering machine.

As a partial substitute for coke breeze, JFE Steel developed a technology for extending the holding time at 1 200 to 1 400°C by injecting a predetermined amount of a hydrocarbon-type gaseous fuel from the surface of the sintering bed⁸⁾, and application of this technology made it possible to improving sinter strength while reducing the coke breeze ratio. JFE Steel also developed a technology for further extending the holding time at 1 200 to 1 400°C and enhancing the effect of gaseous fuel injection by controlling the combustion rate of the coke and gaseous fuel by combined injection of the gaseous fuel and O₂ $^{9,10)}$.



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³ Staff Deputy General Manager, Ironmaking Technology Sec., Ironmaking Dept., East Japan Works (Keihin), JFE Steel This report describes the basic study of the gaseous fuel injection technology and the technology for combined use with O_2 , together with the application of these technologies to actual sintering machines.

2. Study of Gaseous Fuel Injection

2.1 Experimental Method

2.1.1 Sintering pot test

First, the effect of gaseous fuel injection on the sintering bed temperature was investigated using a sintering pot test device. The sintering raw materials were charged in a quartz glass pot ($300 \text{ mm}\phi \times 400 \text{ mmH}$), and liquefied natural gas fuel (hereinafter, LNG; CH₄/ C₂H₆/C₃H₈ = 89/5/6 vol%) was mixed with air and injected from 60 s after ignition until the completion of sintering. The suction pressure was held constant at 6.9 kPa, and the hearth layer thickness was set at 20 mm. Thermal images were captured by thermography from the side surface of the quartz glass pot.

The sintering mixture was adjusted so that the return fine ratio was 20 mass%, the SiO₂ content was 4.8 mass% and basicity (CaO/SiO₂) was 1.9. In the conventional method, the coke breeze ratio was set at 5.0 mass%. However, in the LNG injection method, the LNG injection rate was set so as to obtain 0.4 vol% LNG relative to the suction air, and the coke breeze ratio was decreased to 4.6 mass% to maintain a constant input heat quantity.

In addition to measurements of shatter strength, reducibility (JIS-RI) and reduction disintegration (JIS-RDI), the hematite, calcium-ferrite and magnetite in the mineral texture and the slag texture were quantified by the powder X-ray diffraction method¹¹).

2.1.2 Actual machine test

The results observed in the laboratory were verified by an actual machine test at East Japan Works (Keihin District) No. 1 Sinter Plant (hereinafter, Keihin No. 1 Sinter Plant). To improve the heat pattern of the upper layer, where sinter strength tends to decrease in comparison with the lower layer, a hood was installed over a range of approximately 1/3 of the strand length in the upstream section of the strand, where the reaction zone is thought to exist in the upper layer, and LNG was injected at a rate of 250 Nm³/h. Granulation moisture was set at 7.6 mass% and the bed height was 650 mm. The pallet speed was controlled so that BTP (Burn Through Point; end point of sintering) was constant. Tumble strength, JIS-RI and JIS-RDI before and after LNG injection were measured. In addition, holes were made in the sidewall of the sintering machine pallet car, and R type thermocouples $(3.2 \text{ mm}\phi \times 1000 \text{ mmL})$ were inserted 500 mm into the bed in order to measure the bed heat pattern.

2.2 Effect of Gaseous Fuel Injection on Sinter Property

Table 1 shows the comparison of sinter productivity and quality with the conventional method and the LNG injection method. As shown in the photographs, when the LNG injection method was used, the red hot region was greatly expanded in comparison with the conventional method. Although the sintering time was slightly extended with the LNG injection method, shatter strength and sinter yield improved by 2.2 % and 3.8 %, respectively. Although JIS-RI normally tends to have an inverse relationship with strength, JIS-RI also improved 5.9 % as shatter strength increased with the LNG injection method. In addition, JIS-RDI improved by 7.8 mass%, which is attributed to the increased strength of the sintered ore.

2.3 Effect of Gaseous Fuel Injection on Heat Pattern

Table 2 shows the observation results of sintering behavior by a video camera and thermography at 250 s after ignition. In the thermography observation results, the red hatched area is the zone where temperatures of 1 400°C or higher were measured. With the conventional method, a temperature zone over 1 400°C was observed, even though the temperature zone over 1 200°C was narrow. However, with the LNG injection method, the temperature zone over 1 200°C expanded upward, and the temperature zone over 1 400°C disappeared. Since the combustion start temperature of LNG is 650 to 750°C, it is thought that these changes occurred because the LNG injected from the bed surface began burning before reaching the combustion position of the coke breeze, and this reduced the cooling effect of air flowing from the upper layer after combustion of the coke breeze. Here, 650 to 750°C is

Table 1 Comparison of sinter productivity and quality between all coke method and LNG injection method $^{\rm 8)}$

	Coke 5.0 mass% (Conventional method)	Coke 4.6 mass% and LNG0.4 vol.% (LNG injection method)			
Macroscopic image of red-hot region with quartz glass pot	Red-hot ↓ region width = 60 mm	Red-hot region width = 150 mm			
Sintering time (min.)	16.0	16.7			
Shatter index (%)	70.7	72.9 (+2.2)			
Sinter yield (%)	69.0	72.8 (+3.8)			
Productivity (t/h·m ²)	1.56	1.64 (+0.08)			
JIS-RI (%)	64.5	70.4 (+5.9)			
JIS-RDI (mass%)	36.1	28.3 (-7.8)			



Table 2 Effect of gaseous fuel injection method on temperature distribution measured by thermography at 250 s after ignition⁸⁾

Fig. 1 Effect of gaseous fuel injection method on temperature distribution with mathematical model at 600 s after ignition⁸⁾

the combustion temperature range of CH₄ which comprises about 90 % of LNG. Moreover, because the coke breeze ratio was reduced with the LNG injection method, it is thought that the temperature zone over 1 400°C disappeared as a result.

To clarify the principles of the gaseous fuel injection method, the authors developed a mathematical model for estimation of the temperature distribution in the sintering bed. In this model, the pressure, temperature and gas velocity were calculated by differential equations based on the conservation laws of mass, enthalpy and momentum, and a combustion rate equation for CH₄ was newly added, considering the rate equations for the general reactions in the sintering bed.

Figure 1 shows the effect of the gaseous fuel injection technology on the temperature distribution at 600 s after ignition. The calculation results and experimental results are in good agreement, and the temperature zone from 1 200 to 1 400°C was expanded by the gaseous fuel injection technology. The results also confirmed that CH₄ burns at 650 to 700°C at a position different from that of coke breeze combustion.



Fig. 2 Change of mineral texture with LNG injection method

2.4 Effect of Gaseous Fuel Injection on Mineral **Texture Formation**

Figure 2 shows the changes in the mineral texture when the LNG injection method was used in the sintering pot test. When the LNG injection was used, the calcium-ferrite texture ratio increased by 1.6 times in comparison with the conventional method, while the low strength slag texture ratio decreased. It is considered that the slag texture ratio decreased with the LNG injection method because the maximum temperature was reduced to no more than 1 400°C, and as a result, decomposition of calcium-ferrite was suppressed. Kissin et al.³⁾ reported that the strength and reducibility of the calcium-ferrite texture are excellent, and the strength and reducibility of the slag texture are inferior. Based on this fact, it is thought that the increase in the calcium-ferrite texture ratio and decrease in the slag texture ratio is one reason for the improvement in strength and reducibility with the LNG injection method.

Temperature (°C)



Fig. 3 Effects of LNG injection method on temperature distribution at Keihin No.1 Sinter Plant⁸⁾



Fig. 4 Change in operational result and quality with LNG injection method in comparison with all coke method⁸⁾

2.5 Effect of Gaseous Fuel Injection on Operation Results at Actual Machine

Next, the effect of gaseous fuel injection on the temperature distribution at Keihin No. 1 Sinter Plant was evaluated. **Figure 3** (a) and (b) show the temperature distributions of the upper layer and lower layer, respectively. As shown in Fig. 3 (a), when the LNG injection method was used, the maximum temperature of the upper layer did not increase, but the holding time over 1 200°C was extended from 134 s with the conventional method to 258 s. On the other hand, as shown in Fig. 3 (b) the maximum temperature of the lower layer was reduced from 1 437°C with the conventional method to 1 370°C by the LNG injection method. This maximum temperature reduction is considered to be due to a reduction of 3.0 kg/t-s in coke breeze consumption. Thus, it can be said that LNG

injection improves the strength of the brittle upper layer, while also improving JIS-RI of the lower layer due to the decrease in coke breeze consumption. Based on this, it is thought that the temperature distribution of the "C-type sintering method²," in which the holding time over 1 200°C is extended without increasing the maximum temperature, can be achieved by the LNG injection method.

Figure 4 shows the changes in the operational results and quality with the conventional method and the LNG injection method. At the same productivity, tumble strength improved by approximately 1 % with the LNG injection method when compared with the conventional method, and accompanying this improvement in tumble strength, coke breeze consumption also decreased by 3.0 kg/t-s. JIS-RI also increased gradually and finally improved by 4 %. The heat balance was calculated based on these test results. The heat inputs were

	Case A		Case B		Case C		Case D	
Coke (mass%)	5.0		4.7		5.0		4.7	
O ₂ (vol.%)	21		21		28		28	
NG (vol.%)	_		0.4		_		0.4	
	Video	Thermo- graphy	Video	Thermo- graphy	Video	Thermo- graphy	Video	Thermo- graphy
Temperature (C) 1 400 1 200 1 000 - 800 - 600 - 400 - 200	Air	(Air + LNG		Air + O ₂	3	Air+LNG+O ₂	0

Table 3 Observation results of combustion behavior in sintering bed by video camera and thermography⁹⁾

the heat of combustion of the coke oven gas in the ignition furnace and the coke breeze in the sintering bed, and the LNG. In comparison with the conventional method, unit energy consumption decreased by approximately 60 MJ/t-s with the LNG injection method. The values of the heat of combustion used here were coke oven gas: 17.6 MJ/Nm³, coke breeze: 27.1 MJ/kg and LNG: 41.6 MJ/Nm³. At the same productivity, energy consumption decreased and at the same time, tumble strength and reducibility increased with the LNG injection method.

3. Combined Injection of Gaseous Fuel and Oxygen

3.1 Experimental Method

3.1.1 Sintering Pot Test

Next, we attempted to extend the holding time at 1 200 to 1 400°C by controlling the combustion behavior of the coke breeze and LNG by combined injection of LNG and O_2^{9} .

First, the effect of O_2 injection on the temperature distribution in LNG injection was investigated using the sintering pot test device. Case A is the Base condition, in which LNG and O_2 were not injected. In Case B, 0.4 vol% of LNG was injected for 300 s beginning 60 s after ignition. In Case C, the O_2 concentration of the suction air was enriched to 28 vol%, and in Case D, LNG and O_2 were injected in combination. Under the conditions where LNG was injected, coke breeze was reduced by the isocaloric equivalent of the injected LNG. The test was conducted using the quartz glass pot described in section 2.1.1, and the red hot region was photographed with a video camera and thermography. The sintering mixture was adjusted so that the return fine ratio was 20 mass%, the SiO_2 content was 4.8 mass% and basicity (CaO/SiO₂) was 1.9.

3.1.2 Actual machine test

An actual machine test of combined LNG and O_2 injection was carried out at East Japan Works (Chiba District) No. 4 Sinter Plant. O_2 piping was installed in the LNG injection hood for use in O_2 enrichment. In this experiment, the condition in which no LNG or O_2 was injected was defined as the Base condition. Under the other conditions, a uniform 0.4 vol% of LNG was injected, and the coke breeze was decreased by an amount corresponding to 4 times the equivalent heat quantity of the LNG. The O_2 concentration was varied in the range from 21 vol% to 30 vol%, and the heat pattern in the sintering bed was measured by the same method as in section 2.1.2.

3.2 Effect of Combined Injection of Gaseous Fuel and Oxygen on Red Hot Region and Bed Temperature Distribution in Various Cases

Table 3 shows the observation results for the red hot region and the temperature distribution in the sintering bed for each case. In Case B, that is, only LNG injection, the red hot region expanded in comparison with Case A (Base condition). In contrast, the red hot region in Case C (only O_2 injection) was narrower than in Case A. In Case D (combined injection), the area of the red hot region expanded further than in Case B.

The oxidation rate equations of coke breeze and LNG (CH₄) are generally expressed as a function of the temperature and O_2 concentration, in which the oxidation rate increases as the temperature and O_2 con-



Fig. 5 Schematic diagram of heat pattern and ignition behavior with each case⁹⁾

centration increase. Because LNG burns at 650 to 750° C in atmospheric air (O₂: 21 vol%), the oxidation rate at 650 to 750° C reaches the value at which combustion occurs. However, when the O₂ concentration exceeds 21 vol%, the temperature at which the oxidation rate reaches the value required for combustion is lower than 650 to 750° C, so the coke breeze and LNG begin to burn at a low temperature.

Figure 5 shows a schematic diagram of the combustion position and temperature distribution for each case. In comparison with Case A, in which only the combustion position of coke breeze exists, the combustion position of LNG is located at a higher position than that of the coke breeze, and as a result, the high temperature zone in the heat pattern expands upward with Case B (only LNG injection). This behavior is as described in section 2.3. On the other hand, in Case C (only O_2 injection), the combustion start temperature of the coke breeze decreases as the O2 concentration increases, and as a result, the combustion position of the coke breeze shifts to the lower layer. In contrast to this, in Case D (combined injection) both the coke breeze and the LNG begin to burn at lower temperatures as the O₂ concentration increases, so the combustion position of the coke breeze shifts downward while the combustion position of the LNG shifts upward. Thus, it is thought that the distance between the combustion positions of the two fuels expands due to the shifts of the two combustion positions, and the high temperature zone in the heat pattern expands.

Figure 6 shows the relationship between productivity



Fig. 6 Relationship between productivity and cold strength in pot test⁹⁾



Fig. 7 Effects of O_2 concentration on temperature with constant LNG concentration: 0.4 vol. $\%^{10)}$

and strength in the pot test. In Case B, sinter strength increased because the holding time at 1 200 to 1 400°C was extended by LNG injection. Conversely, in Case C, productivity increased because the sintering time was shortened by O_2 enrichment. In Case D, due to the synergistic effect of combined LNG and O_2 injection, sinter strength exceeded the result in Case B while productivity exceeded that in Case C, resulting in broad improvements in both sinter strength and productivity.

3.3 Effect of Combined Injection of Gaseous Fuel and Oxygen on Operational Results at Actual Machine

Figure 7 shows the results of measurements of the heat pattern. Since extending the holding time at 1 200 to 1 400 °C is effective for improving sintered ore quality, as mentioned previously, the holding time at 1 200 to 1 400 °C was measured. In comparison with the base condition T1, the holding time at 1 200 to 1 400 °C increased by 60 s under condition T2 (LNG injection). Under condition T3, when the O₂ concentration was enriched to 25 vol%, the holding time increased by 100 s in comparison with T2, and under condition T4, with O₂ enrichment to 27 vol%, the holding time increased by an additional 116 s in comparison with T3. On the other hand, under T5, where O₂ enrichment was increased to 30 vol%, there was almost no increase in comparison with T4. In this case, it is thought that the



Fig. 8 Comparison of sinter strength between before and after application¹⁰⁾

further increase in O_2 enrichment did not contribute to extension of the holding time at 1 200 to 1 400°C because the separation between the combustion positions of the coke breeze and the LNG was too large.

Figure 8 shows the results of the operational test. During this test period, the condition of 0.4 vol% injection of LNG was defined as the Base case, and O_2 injection for enrichment up to 27 vol% was performed. Under the condition of a constant sinter cake productivity (constant pallet speed), tumble strength was increased from 63.1 % to 64.3 % by O_2 injection. In addition, the sintering rate increased due to the increase in the O_2 concentration, and burnt lime consumption decreased from 10 kg/t-s to 8 kg/t-s.

4. Conclusion

To reduce CO₂ emissions, JFE Steel developed a gaseous fuel injection technology for the sintering machine (Super-SINTERTM) and a combined gaseous fuel and O₂ injection technology (Super-SINTERTM OXY).

- (1) The gaseous fuel injection technology extends the holding time at 1 200 to 1 400°C by combustion of the gaseous fuel injected from the surface of the sintering bed before it reaches the combustion point of the coke breeze.
- (2) The combined gaseous fuel and O₂ injection technology further extends the holding time at 1 200 to 1 400°C by expanding the distance between the combustion positions of the coke breeze and the gaseous fuel by utilizing O₂ enrichment to lower the

combustion start temperature of the coke breeze and gaseous fuel.

- (3) It is considered that extension of the holding time at 1 200 to 1 400°C improves sinter strength by increasing the calcium-ferrite texture and reducing the slag texture.
- (4) Application of both technologies to actual sintering machines was completed, and the strength improvement effect was confirmed. At Keihin No. 1 Sinter Plant, a reduction of CO₂ emissions by a maximum 60 000 t/y was achieved by the introduction of the Super-SINTERTM technology.

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