

# Improvement of Blast Furnace Reaction Efficiency by Temperature Control of Thermal Reserve Zone

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## Abstract

*The temperature control of the thermal reserve zone was studied as a technology for drastically improving the reaction efficiency of a blast furnace, and use of high-reactivity coke and carbon-containing ore agglomerate was proposed therein. For the study of the effects of their use, an adiabatic blast furnace simulator was developed as a test apparatus capable of simulating the change in the furnace temperature and gas volume resulting from reactions between them in coexistence with each other. Tests using the developed simulator yielded the following findings. The starting temperature of the reaction of the coke and carbon in the ore agglomerate corresponds to the temperature of the thermal reserve zone. The thermal reserve zone temperature lowers as the reactivity of coke and the carbon in the agglomerate increases. The reaction efficiency of a blast furnace improves with (a) the use of high-reactivity coke, (b) an increase in its rate of use, (c) a decrease in its size and (d) its mixed charging in ore layers. The use of high-reactivity coke can decrease the reducing agent rate (RAR) by approximately 25 to 33 kg/t. The mechanisms by which the use of high-reactivity coke improves the efficiency of furnace inner reactions include (1) control of the FeO-Fe reduction equilibrium point (W point), or lowering of the thermal reserve zone temperature, (2) higher reduction ability of gas due to higher reactivity of coke, (3) accelerated ore reduction by gas due to (i) the reduction of FeO into Fe at lower temperatures, (ii) an increase in the volume of fine pores in ore grains and (iii) a decrease in the melt formation resulting from a decrease in calcio-wustite (CW). The tests also confirmed that use of carbon-containing ore agglomerate was promising for controlling the thermal reserve zone temperature.*

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### 1. Introduction

A high-temperature thermal reserve zone forms in a blast furnace portion where the burden temperature is 950 to 1,000°C. When the temperature of the zone is equal to the W point (wustite-iron reduction equilibrium point) of the RIST diagram<sup>1)</sup>, the shaft efficiency of a blast furnace becomes 100%, theoretically. In the current blast furnace operation, the shaft efficiency is as high as over 90% of the theoretical efficiency.

To further improve the efficiency of furnace inner reactions, it is necessary (i) to shift the operation curve (the dotted line AP in Fig. 1) towards the W point, maintaining the present temperature condition of the thermal reserve zone unchanged (A → B), or (ii) to lower the thermal reserve zone temperature, shift the W point towards the high- $\eta_{CO}$  side ( $\eta_{CO} = CO_2 / (CO + CO_2)$ ), increase the reduction driving force, which is the difference between actual  $\eta_{CO}$  and the  $\eta_{CO}$  at the reduction equilibrium point, and thus, accelerate the reduction of ore (B → C). The principal measures conventionally practiced, such as the improvement of the reducibility of sinter, the high-temperature properties of ore layers (mixing of nut coke in ore layers, etc.) and the gas flow distribution through control of burden distribution, aimed at (i) above. The measures aiming at (ii) above are limited to the use of high-reactivity coke<sup>2)</sup> and that of carbon-containing ore agglomerate in a large quantity<sup>3)</sup>, which we proposed.

This paper describes the concept and effects of technology of controlling the temperature of the thermal reserve zone as a promising measure to decrease the CO<sub>2</sub> emission.

### 2. Improvement in Reaction Efficiency of Blast Furnace with High-reactivity Coke<sup>2)</sup>

#### 2.1 Reduction behavior of sinter and improvement of its reducibility with high-reactivity coke

The use of high-reactivity coke is a technology that aims at controlling the temperature of the thermal reserve zone and the reduction equilibrium point of a blast furnace by lowering the reaction starting temperature of coke as well as accelerating indirect reduction of ore agglomerate by increasing the reduction potential at high temperatures. To confirm the effect of the technology, a counter-flow, moving-layer type adiabatic blast furnace inner reaction simulator (BIS) (see Fig. 2)<sup>3)</sup> was developed. The reaction tube is a stainless steel pipe

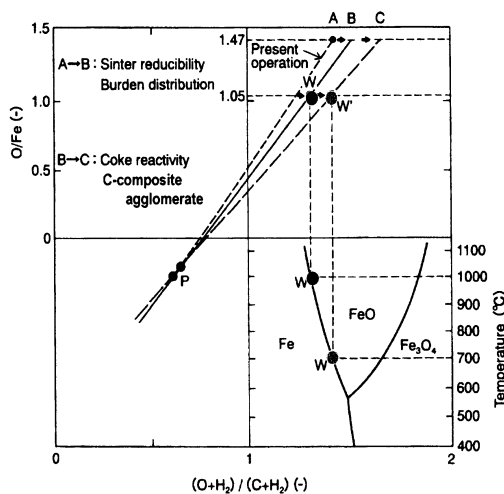


Fig. 1 Improvement technology of reaction efficiency on a blast furnace (RIST diagram)

103 mm in inner diameter and 5.4 m in height. The electric furnaces consist of four heating furnaces that preheat the gas to the temperature of the upper cohesive zone of a blast furnace (1,200°C) and complete the reduction of ore and 10 heat-insulating furnaces that make the reactions and heat transfer at temperatures lower than the above temperature proceed in an adiabatic system.

Table 1 shows the properties of the sinter and coke used for the test and the test conditions. The sinter, produced on a commercial sintering machine, had a reduction index (RI under JIS) of 66% and a total porosity of 32%, and its grain size ranged from 10 to 15 mm. In consideration of the circulation and adhesion of alkali in a blast furnace, coke having an alkali content of 2% and a JIS reactivity of 59 was prepared as the normal coke sample, and other coke samples having different JIS reactivity values were also prepared. Because of the limited inner diameter of the reaction tube, coke grains 10 to 15 mm in size were regarded as coarse lump coke, and those 3 to 5 mm in size as nut coke.

Fig. 3 shows the furnace temperature and the reduction behavior of sinter with coke having different reactivity indices. The temperature of the thermal reserve zone fell as the reactivity of coke increased: whereas the thermal reserve zone temperature was approximately 1,000°C with the normal coke having a JIS reactivity index of 59, it fell to approximately 900°C with high-reactivity coke having a JIS reactivity index of 93 to 98.

As for the reduction behavior of sinter, whereas from the furnace top to the thermal reserve zone the reduction degree changed in substantially the same manner irrespective of the reactivity of coke, in the furnace zone hotter than the thermal reserve zone, the reducibility of sinter improved as the reactivity of coke increased.

Fig. 4 shows the analysis results of blast furnace inner reaction indices using the RIST model<sup>4)</sup>. The indirect reduction degree of sinter (the utilization rate of furnace top gas  $\eta_{CO}$ ) increased and the solution loss of coke decreased as the JIS reactivity of coke increased, and the reaction efficiency relative to the thermal reserve zone tem-

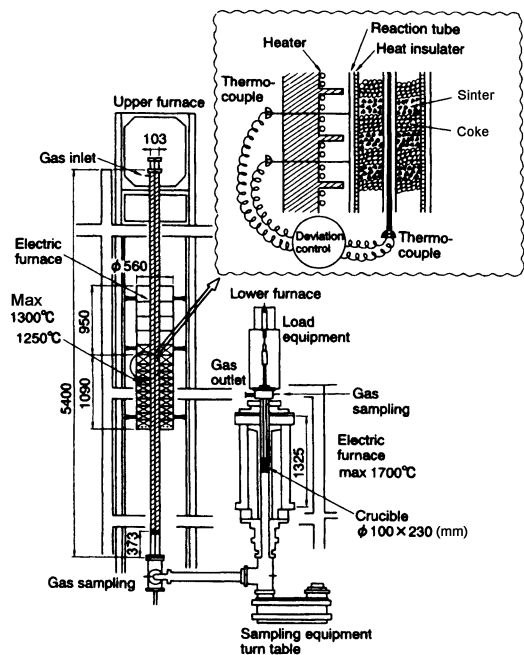


Fig. 2 Schematic representation of the adiabatic blast furnace simulator (adiabatic BIS)

Table 1 Chemical composition and physical properties of sinter and coke

a) Sinter				(wt%)		(%)	
T.Fe	FeO	CaO	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	MgO	JIS - RI	Total porosity
57.56	5.03	8.9	5.22	1.89	1.69	66	32

b) Coke						
Sample	K	Na	Fe <sub>2</sub> O <sub>3</sub>	CaCO <sub>3</sub>	JIS - Reactivity	
LC-1	0.26	0.05	0	0	22	
LC-2	1.28	0.06	0	0	50	
NC	2.08	0.15	0	0	59	
HRC	4.12	0.97	0	0	93 - 98	
Fe <sub>2</sub> O <sub>3</sub> - HRC	2	0	4	0	98	
CaCO <sub>3</sub> - HRC	2	0	0	4	95	
Formed coke	2	0	0	0	92	

LC: Low reactivity coke, NC: Normal coke, HRC: High reactivity coke

c) Operational conditions

RAR (Reducing agent rate) 480 kg/t  
 BG (Bosh gas volume) 1 363 Nm<sup>3</sup>/t  
 Gas composition CO: 35.6%, H<sub>2</sub>: 4.4%, N<sub>2</sub>: 60.0%

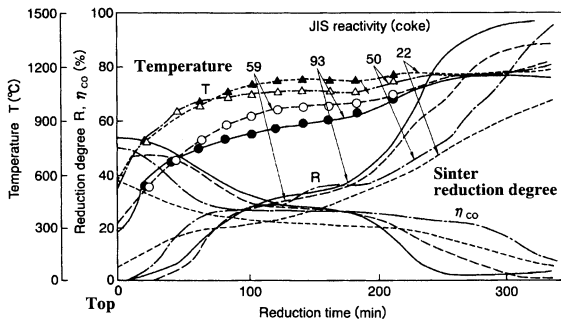


Fig. 3 Influence of coke reactivity on the temperature and sinter reduction behavior

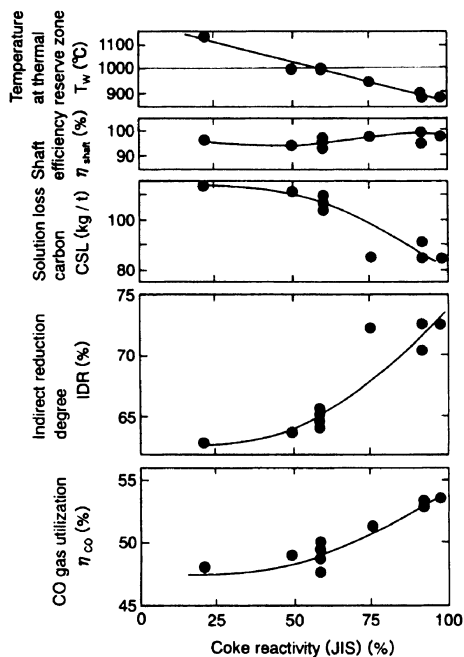


Fig. 4 Influence of coke reactivity on the reduction index

perature also increased. This indicates that the wustite-iron reduction equilibrium point (W point) is expected to shift towards the lower-temperature side as the reactivity of coke increases, and the operation curve of Fig. 1 towards the new W point with high-reducibility sinter.

To study a method for effective use of high-reactivity coke, an investigation was conducted on the blast furnace inner reaction indices by mixing coarse and fine grains of high-reactivity coke (JIS reactivity 98) in the coke and sinter layers by different mixing ratios.

Fig. 5 shows the results of our reduction analysis using the RIST model. The thermal reserve zone temperature fell and the reduction rate of sinter from the lower end of the thermal reserve zone to high temperature zones increased as the mixing ratio of the high-reactivity coke increased or as its size became smaller with the same mixing ratio. The improvement effect of reaction efficiency due to a decrease in the thermal reserve zone temperature was more prominent as the mixing ratio of the high-reactivity coke increased and as its grain size decreased. The blast furnace inner reduction indices with mixing of fine high-reactivity coke by 25% were substantially the same with those with mixing of coarse high-reactivity coke by 50%. This indicates that high-reactivity nut coke exerts far greater improving effects on blast furnace inner reactions than coarse lump coke does.

The test results also showed that the mixing of the high-reactivity coke in sinter layers was more effective in improving the reduction indices than its mixing in coke layers, indicating that the mixing of the high-reactivity coke in sinter layers accelerated the reduction of sinter more effectively.

Based on these fundamental test results, test use of high-reactivity coke is being conducted on commercially operated blast furnaces.

2.2 Mechanism of sinter reduction efficiency improvement by lowering thermal reserve zone temperature

A comparison of the structure of sinter reduced with high-reactivity coke with that reduced with normal coke revealed difference in the reduction behavior of calcium ferrite, a constituent structure of sinter.

With high-reactivity coke, the peak of the reduction rate of sinter shifts to the lower-temperature side, and so do the starting tempera-

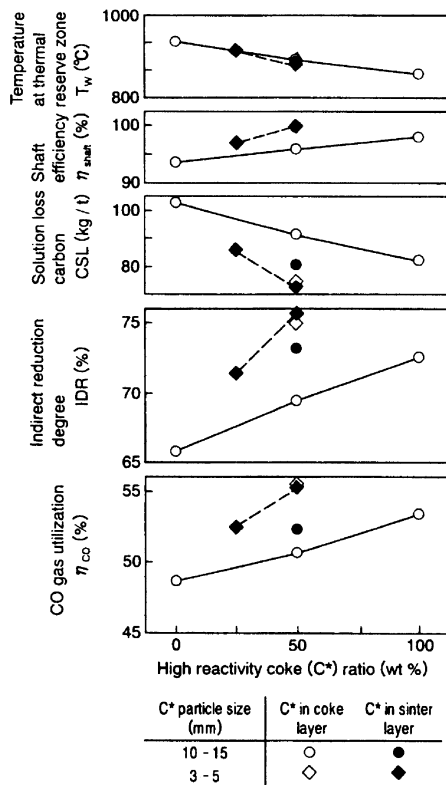


Fig. 5 Influence of mixing ratio, size and charging method of high reactivity coke on the reduction index

tures of the reduction from wustite to iron and that from the wustite structure of calcio-wustite (CW) to iron. What is more, a structure forming from the reduction of the CW into iron was found in a large quantity in the temperature range higher than the thermal reserve zone temperature (see Fig. 6).

The melt formation and pore structure of sinter in the high-temperature reduction zone were investigated using normal coke, and clarified that the melt began to form in sinter grains from roughly 1,100°C to clog pores partially, and as a result, the high-temperature reduction rate of sinter began to decrease from roughly 1,150°C, and that the primary melt formed near a CW structure<sup>5)</sup>. To improve the

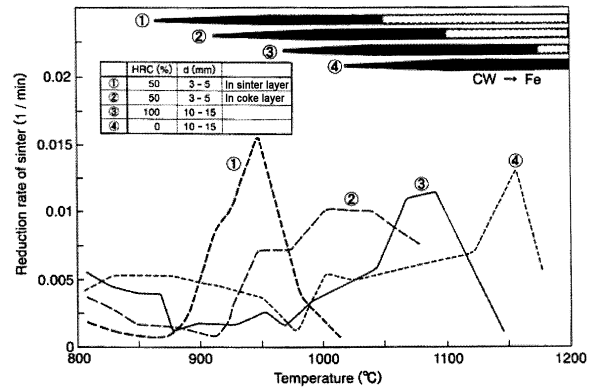


Fig. 6 Influence of mixing ratio, size (d) and charging method of high reactivity coke on reduction rate of sinter and starting temperature of reduction from calcio-wustite (CW) to iron

efficiency of sinter reduction, it is important to (1) accelerate the reduction reactions in a temperature range of 1,150°C or below, where micro pores form markedly and the melt does not adversely affect the reactions, or (2) decrease the CW structure, which causes the melt formation. The use of high-reactivity coke is effective in both (1) and (2) above.

A comparison of the reaction amounts of coke in temperature ranges 1,150°C or lower and above shows that, with high-reactivity coke, the reaction amount of coke is large at 1,150°C or lower, but it decreases in the high-temperature range above 1,150°C, and the total solution loss of coke is smaller than that with normal coke (see Table 2). The increase in the coke consumption at 1,150°C or lower is due to the fact that the coke begins to react from lower temperatures and the coupling reactions ( $CO_2 + C = 2CO$ ,  $FeO + CO = Fe + CO_2$ ) proceed prominently. The decrease in the coke consumption at temperatures above 1,150°C, on the other hand, is because the coupling reactions reduce sinter at the lower temperatures, and as a result of the early consumption of sinter, only a small amount of sinter is left for the reduction at the higher temperatures, and there is only a small amount of  $CO_2$  for the high-reactivity coke to react with.

Summarizing the above, the efficiency improvement of blast furnace inner reactions can be attributed to the use of high-reactivity coke to the factors such as the following:

Table 2 Furnace temperature and solution loss carbon by using high reactivity coke

Sinter	Sample	d coke (mm)	HRC ratio (%)	Mixed layer	Solution loss carbon (kg/t)		
					Temp. of TRZ - 1 150°C	1 150°C -	Total
NS	NC	10-15			43	60	103
HRS	NC	10-15			67	16	83
NS	HRC	10-15	100		54 - 76	6 - 25	82
NS	HRC	10-15	50	Coke	67	25	92
NS	HRC	10-15	50	Sinter	79	2	81
NS	HRC	3 - 5	50	Coke	69	6	75
NS	HRC	3 - 5	50	Sinter	71	2	73
NS	HRC	3 - 5	25	Sinter	71	15	86
NS	Fe <sub>2</sub> O <sub>3</sub> - HRC	10-15	100		68	7	75
NS	CaCO <sub>3</sub> - HRC	10-15	100		66 - 77	18 - 22	84
NS	Formed coke	10-15	100		64	20	84

NS: Normal sinter, HRS: High reducibility sinter (total porosity 56%), TRZ: Thermal reserve zone

- (1) High-reactivity coke begins to react at temperatures lower than normal coke does, and as a result, it is possible to lower the W point temperature.
- (2) Lowering the thermal reserve zone temperature accelerates the reduction of FeO and CW into Fe at lower temperatures at which the fine pores begin to increase (the reduction rate of sinter in the temperature range of 1,150°C or lower is roughly 1.5 times the reaction rate of the solution loss of coke).
- (3) Accelerating the reduction of CW into Fe decreases CW, which turns into primary melt at approximately 1,100°C to clog pores, and thus improves the reduction of sinter in the higher temperature range.

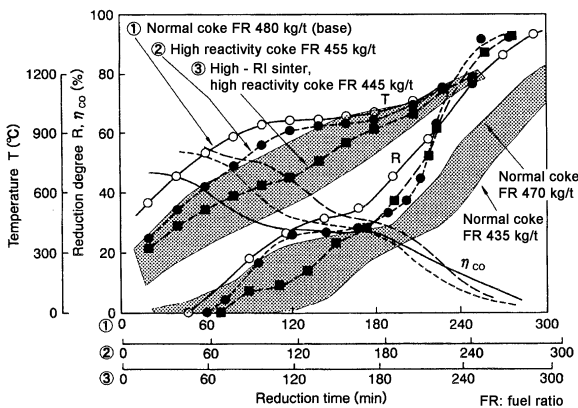
**2.3 Reducing agent rate lowering effect with high-reactivity coke**

The above investigation clarified that the use of high-reactivity coke was effective in enhancing the efficiency of blast furnace inner reactions. At this, estimates were made for the decrease in the reducing agent rate (RAR) by the use of high-reactivity coke based on the thermal reserve zone temperature shown in Fig. 5 and the shaft efficiency figure at the temperature (see Table 3).

With high-reactivity coke, it is possible to decrease the RAR by 20 to 30 kg/t from that with normal coke (480 kg/t). When the shaft efficiency is further improved through combined use of high-reactivity coke with high-reducibility sinter, it will be possible to further decrease the RAR from the above figure by about 10 kg/t. To verify the estimated RAR decrease, tests were done on the adiabatic BIS using two combinations of burdens, high-reactivity coke + normal sinter (estimated RAR of 450 to 460 kg/t, namely a decrease by roughly 25 kg/t) and high-reactivity coke + high-reducibility sinter (estimated RAR of 445 to 450 kg/t, namely a decrease by roughly 35 kg/t). Fig. 7 shows the results. For comparison purposes, the graph also shows the simulation results of low-RAR operation with the same sinter and normal coke (RAR 435 and 470 kg/t). Generally

**Table 3 Prediction of operational data by using high reactivity coke**

Sinter	Coke	$\eta$ shaft (%)	Temperature of TRZ (°C)	RAR (kg/t)
NS	NC	94	1 000	480
HRS	NC	100	1 000	460 - 470
NS	HRC	99	900	450 - 460
HRS	HRC	100	900	445 - 450



**Fig. 7 Sinter reduction behavior by using high reactivity coke on the operational condition of the low RAR**

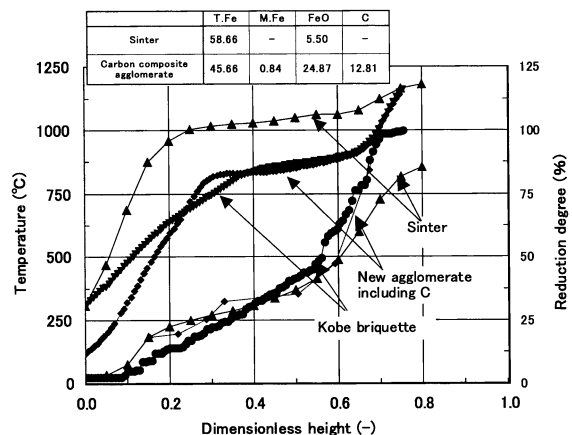
speaking, the temperature in the entire furnace decreased and the position where the reduction of sinter started shifted to the lower side as the RAR decreased.

Whereas, with normal coke, the reduction rate of ore in the thermal reserve zone and below (on the higher-temperature side) decreased, and the reduction became markedly insufficient compared with the ore reduction at a RAR of 480 kg/t, with high-reactivity coke, the ore reduction at the lower end of the thermal reserve zone and below was significantly accelerated, and as a result, the position where a reduction degree of 90% was attained was substantially the same as in the base case (with normal coke and sinter) or somewhat higher (on the lower-temperature side). This means that a sufficient ore reduction capacity was maintained with high-reactivity coke even under low-RAR operation, and we concluded that a decrease in the RAR by 25 to 35 kg/t was possible.

**3. Improvement in Reaction Efficiency of Blast Furnace with Carbon-containing Ore Agglomerate<sup>3)</sup>**

The “study project for halving energy consumption of blast furnaces” conducted from 1999 to 2004 under Government auspices covered a wide variety of aspects regarding the kind and amount of carbon to be included in ore agglomerate and the reduction rate of such carbon-containing ore agglomerate. The studies included theoretical examination of the reduction rate of carbon-containing ore agglomerate (the coupling reactions), investigations into the reduction and melting behavior of the agglomerate in a high-temperature field and its shapes (botryoidal, quasi-tetrahedral, etc.), and the production method and reduction and carburizing behavior of high-strength, hot-briquetted, carbon-containing ore agglomerate.

Under the framework of the project, the shape of the carbon-containing ore agglomerate was investigated to examine the in-furnace reduction behavior of such agglomerate using the adiabatic BIS. Fig. 8 shows the results. The studies confirmed that, whereas the thermal reserve zone temperature could be lowered only to about 900°C with normal sinter and high-reactivity coke, it could be lowered further to about 820°C when carbon-containing ore agglomerate was used, and additionally that the carbon-containing ore agglomerate improved the furnace inner reactions. These findings are expected to contribute to the development of next-generation blast furnace technology to control the thermal reserve zone temperature (reduction equilibrium temperature).



**Fig. 8 Reduction behavior of carbon-contained agglomerates in a simulation of an actual furnace operation using BIS**



#### 4. Summary

To accurately estimate the reaction behavior of sinter and coke in a blast furnace, an adiabatic blast furnace inner reaction simulator was developed to verify the influences of high-reactivity coke and carbon-containing ore agglomerate over the temperature of the thermal reserve zone and to verify their reaction efficiency improvement effects using the simulator. The studies yielded the following findings:

- (1) The thermal reserve zone temperature falls and the efficiency of furnace inner reactions improves as the reactivity of coke improves. The thermal reserve zone temperature can be controlled by controlling the reactivity of coke.
- (2) The efficiency of furnace inner reactions improves as the mixing ratio of high-reactivity coke increases; the improvement effect increases further when small grains of high-reactivity coke are mixed in the sinter layers.
- (3) According to our estimation, the use of high-reactivity coke lowers the reducing agent rate by about 25 to 35%, depending on the quality of sinter.
- (4) The factors for the efficiency improvement of the blast furnace inner reactions by the use of high-reactivity coke include the

following: (i) high-reactivity coke begins to react at lower temperatures than normal coke does, and as a result, the  $\gamma$  co at the FeO-Fe reduction equilibrium increases; (ii) the pores that form in sinter through its reduction into Fe at low temperatures tend to be fine, and these pores contribute to improving reduction rate; and (iii) the use of high-reactivity coke lowers the reduction starting temperature of the wustite structure of calcium ferrite (calcio-wustite (CW)) into Fe and this quickly decreases CW, which turns into melt to clog pores, contributing to improving the high-temperature properties of sinter.

- (5) Use of carbon-containing ore agglomerate in a large quantity lowers the thermal reserve zone temperature to about 820°C and improves the efficiency of furnace inner reactions.

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