Decreasing Coke Rate under All-Pellet Operation in Kobe No.3 Blast Furnace

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Having no coke plant, Kobe Works of Kobe Steel aimed at low coke-ratio operation of its blast furnace process. Furthermore, its sintering plant was closed in 1999, and the process was converted to all-pellet operation in 2001. Afterward, the plant was using self-fluxed dolomite pellets produced at and shipped from Kakogawa Works. Kobe Works was the only site in Japan that adopted and continued all-pellet operation and optimized the complex control of burden distribution in accordance with the high pellet ratio and pulverized coal combustion in accordance with the multi-brand coal types, which it did in the 4th blast furnace (inaugurated in 2007). Furthermore, replacing lump ore with self-fluxed dolomite pellets has improved the meltdown property of iron ore at high temperature. As a result, operation at a low coke rate of 283 kg/tonne was achieved under the severe conditions of a high pellet ratio (80%) and raw materials that were all stored in the yard.

Introduction

Kobe Steel started operation as an integrated iron and steel works in 1959 with the firing of the No.1 blast furnace at Kobe Works. After that, Kobe Works began operating a three-blast furnace system, but in 1983, it shifted to a single blast furnace system consisting of the No. 3 blast furnace only. After experiencing the Great Hanshin-Awaji Earthquake in 1995, Kobe Works carried out blast furnace renovation work in 2007, and the No. 3 blast furnace (hereinafter referred to as the "Kobe No. 3 blast furnace") was put into operation. However, the Kobe No. 3 blast furnace was shut down on October 31, 2017 to consolidate the upstream processes at Kakogawa Works in order to strengthen the profitability of the Iron and Steel Business division. This closed the 59-year history of blast furnace operation at Kobe Works.

In October 2016, one year before the Kobe No. 3 blast furnace was shut down, the technologies cultivated till then were applied together to achieve low coke rate operation at 283 kg/tonne under the harsh conditions of 80% pellet composition and raw materials that had all been stored in the yard. This paper reports on the concept and history of the operation.

Table 1 Comparison of properties between sintered ores and pellets for blast furnace burden

	Advantages	Disadvantages
Sintered ores (Crushed sizing)	High inclination angle High reducibility	Wide size range High reduction degradation
Pellets (Pelletizing)	Low slag rate Low reduction degradation	Low inclination angle Retardation of reduction

1. Features of raw materials used in Kobe No. 3 blast furnace

Kobe Works had no coke oven and purchased coke from outside. It was forced to use coke that was more expensive than that used by other ironworks. For this reason, the blast furnace operation of Kobe Works aimed at low coke-ratio operation. Also, in response to the construction of a power generation plant in the Kobe Works, its sintering plant was closed in 1999, and the process was converted to all-pellet operation (pellet ratio 73%, lump ore 27%) in 2001.[1)] **Table 1** compares the properties of sintered ores and pellets. Pellets generally have drawbacks in high-temperature properties compared with sintered ore. Kobe Steel has been producing self-fluxed dolomite pellets with improved quality by adding dolomite at the pellet plant of Kakogawa Works. The Kobe No. 3 blast furnace used these pellets to realize low coke rate operation.

Then, at the Kobe No. 3 blast furnace, Kobe Works optimized the complex control of burden distribution in accordance with the high pellet rate, and pulverized coal combustion in accordance with the multi-brand coal types.[2)] Furthermore, replacing some parts of lump ore with self-fluxed dolomite pellets[3)] improved the meltdown property of burden materials at high temperature. These and other efforts enabled all-pellet operation, the only example in Japan, to continue in a stable manner.

2. Concept of decreasing coke rate under all-pellet operation

Fig. 1 shows the concept of reducing the coke rate under all-pellet operation. There are two possible measures to use against the changes in the in-furnace

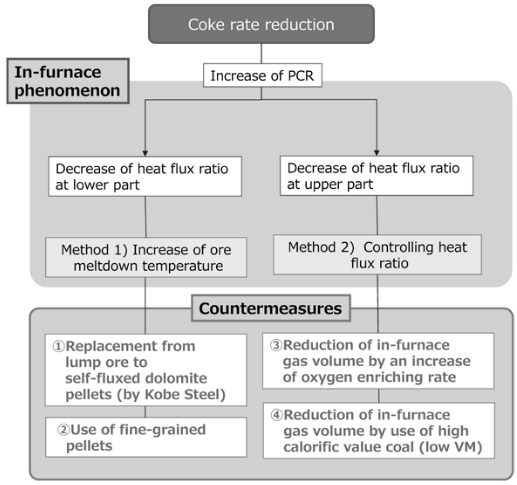

Fig. 1 Concept of coke rate reduction in all-pellet operation

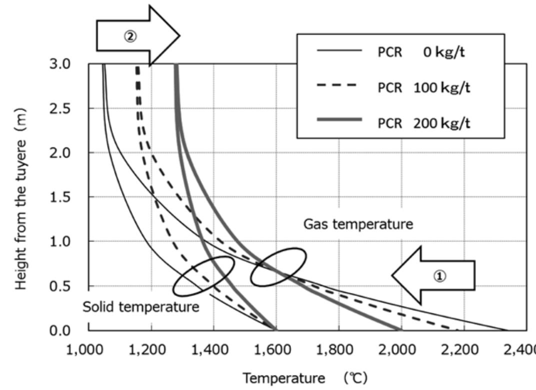

Fig. 2 Changes of solid and gas temperature in lower part of furnace with pulverized coal injection

phenomena when the coke rate is decreased: raising the ore melt down temperature and adjusting the heat flow ratio (the heat capacity of falling burden material/the heat capacity of furnace top gas).

Both of the measures were implemented in the low coke rate operation this time, and this section mainly focuses on the measures for raising the ore melt down temperature.

2.1 Effect of internal volume of blast furnace on ore melt down control

In general, the furnace height decreases as the internal volume of the blast furnace decreases. For this reason, the height from tuyeres to the bottom of the furnace bosh also tends to decrease. As a result, when the unreduced ore in the periphery collapses, the possibility of unreduced FeO reaching a tuyere increases, raising the risk of breaking down the tuyere. In particular, the body of a small blast furnace with an internal volume of 3,000 m^3 or less has a heat capacity smaller than a large blast furnace body has, and it is more important to control the melt down properties of the peripheral ore at high temperatures. Since the Kobe No. 3 blast furnace was a small blast furnace (inner volume of furnace: 2,112 m^3), efforts were made to improve the high temperature melt down properties of the peripheral ore.

2.2 Melt down properties of ore required for an increased amount of injected pulverized coal

To reduce the coke rate, it is necessary to increase the amount of pulverized coal, a substitute reductant, injected from tuyeres. **Fig. 2** shows the results of calculating the temperature changes of solid and gas, assuming that the lower part of the blast furnace is the field for the heat exchange of the solid and gas that have completed chemical reactions. Even when the gas temperature before a tuyere decreases with the increase of the pulverized coal ratio (① in Fig. 2), and if the molten iron temperature is kept constant, the temperature rises in the lower furnace part (② in Fig. 2). In order to maintain the ventilation of the lower furnace part while raising its temperature, it is considered to be necessary for the pellets to melt down at a higher temperature. Hence, to reduce the coke rate under this all-pellet operation, the lump ore was replaced with self-fluxed dolomite pellets with excellent high-temperature melt down properties to improve the high-temperature melt down characteristics in the periphery.

3. Concept of burden distribution control to decrease coke rate

3.1 Four-batch charging of ore to improve accuracy of burden distribution control and peripheral charging of fine pellets

Fig. 3 shows the configuration of the furnace-top charging device of the Kobe No. 3 blast furnace.[4] The charging is performed by a bell-less system of two-parallel top hopper type. Fig. 3 (a) shows the movement when the coke is charged in the center, and Fig. 3 (b) shows the movement of the distributing chute when the ore is charged.

Fig. 4 shows the method of controlling burden distribution for low coke rate operation. In 2-batch charging of coke and ore using the bell-less charging device, center coke charging was implemented (Fig. 4 (a)). The following three points are particularly important in all-pellet operation:

(1) Forming a flat part of coke layer and ore layer in the periphery.

(2) Smoothing the ratio, $L_O/(L_O + L_C)$(hereinafter

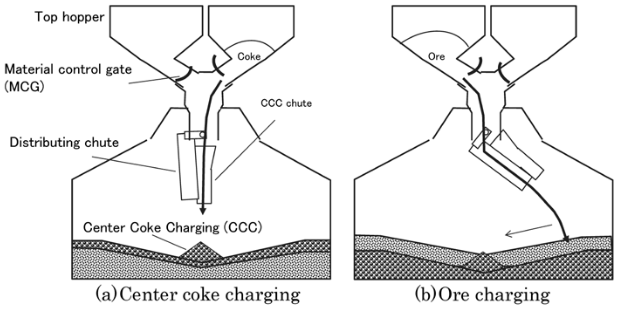

Fig. 3 Furnace-top charging device for Kobe No. 3 blast furnace

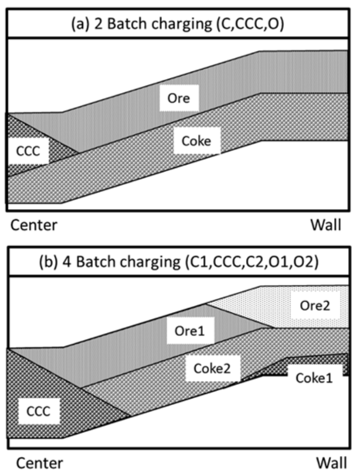

Fig. 4 Scheme of burden distribution control for low coke rate operation

referred to as "layer thickness ratio") of ore layer thickness L_O and ore and coke layer thicknesses $L_O + L_C$ in the radial direction of the furnace throat in the periphery to prevent pellets from flowing in.

(3) In the parallel two-stage hopper, the circumferential balance must be controlled precisely.

Fig. 5 is a conceptual diagram of burden distribution control in all-pellet operation. This burden distribution control enabled the optimization of the surrounding gas flow while maintaining a strong central gas flow. Furthermore, the gas utilization rate (CO_2 % / (CO % + CO_2 %), hereinafter referred to as η CO) of the furnace-top gas was increased, allowing the reductant rate to be decreased.

Fig. 6 shows the change over time in the diameter of coke grains discharged from the furnace top hopper. The coke diameter was determined by image analysis of coke being discharged from an actual machine. Particularly for the center charged coke that forms the deadman coke, the coke grains with large diameters at the end of the discharge were used.

For this all-pellet operation, it was necessary to improve the control accuracy of the burden

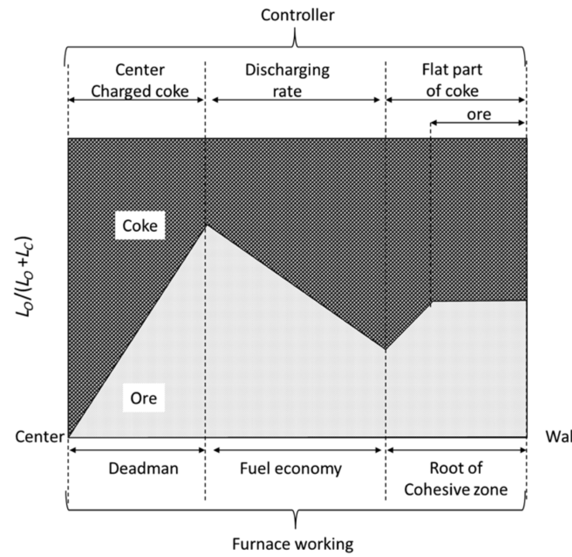

Fig. 5 Concept of burden distribution control for Kobe No. 3 Blast Furnace

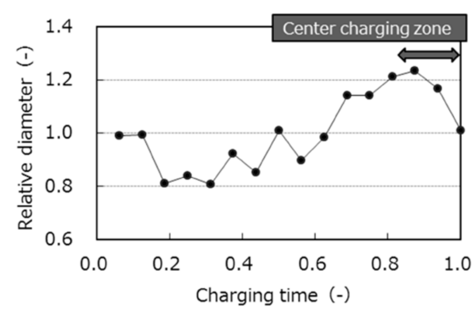

Fig. 6 Change with time of diameter of coke charged from furnacetop hopper

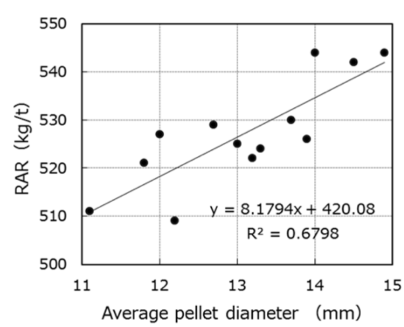

Fig. 7 Influence of average diameter of pellet on reducing agent rate (RAR)

distribution on the side of the ore in order to replace lump ore with self-fluxed dolomite pellets. Hence, the conventional 2-batch charging (pellet 65%) was converted to 4-batch charging[5] (pellet 80%) (Fig. 4 (b)).

Fig. 7 shows the effect of the average diameter of the pellets on the reducing agent ratio.[6] It can be seen that the smaller the average diameter of the pellets, the better the reducibility and the lower the reductant rate. In this all-pellet operation, fine pellets with small diameters (3 to 6 mm) and excellent reducibility were mixed (1.8%) at the time of the second batch charging and were selectively charged into the periphery in order to improve the ore melt down properties in the periphery.

3.2 Relationship between burden distribution in furnace throat and gas flow in lower furnace part

Controlling the shape of the cohesive zone through the airflow resistance distribution in the shaft is of significant importance in the burden distribution in the furnace throat. Meanwhile, from the viewpoint of the function of the lower furnace part, the importance of the burden distribution is that it regulates the amount of inflow in the radial direction of the lower furnace part of coke, which is the only filling structure.

Fig. 8 shows the change in the layer thickness ratio between the conventional 2-batch charging and 4-batch charging. Despite the increased amount of pellet, the distribution of the layer-thickness ratio from the middle to the periphery is smoothed, with almost no change in the layer thickness ratio in the center, which successfully avoided the destabilization of burden distribution due to the increased amount of pellets.

Fig. 9 shows the rate of coke supplied to the lower furnace part, which corresponds to the layer thickness ratio distribution in the furnace throat.[7] The rate of coke supplied at the lower part of the furnace was the value obtained by subtracting the carbon consumption (solution loss, carburization and metalloid reaction) from the coke rate in the diameter direction, which corresponds to the layer thickness ratio distribution in the furnace throat. When the layer thickness ratio exceeds 0.7, the rate of the coke supplied to the lower furnace part becomes almost zero, the coke slit disappears locally, and the gas distribution function decreases. When the layer thickness ratio of the periphery exceeds 0.7 to in order to strongly suppress the peripheral gas flow, the heat dissipated from the furnace body increases, and the gas flow tends to become unstable due to the formation of an S-shaped cohesive zone.[8] Therefore, the burden distribution was adjusted to make the layer thickness ratio 0.7 or less.

In this all-pellet operation, upon replacing lump ore with self-fluxed dolomite pellets, the accuracy of burden distribution control on the side of the ore was improved by the 4-batch charging to prevent the pellets from flowing in. Furthermore, from the change in the η CO distribution in the furnace throat during the low coke rate operation (**Fig.10**), it can be said that the peripheral η CO was improved by the peripheral charging of fine pellets.

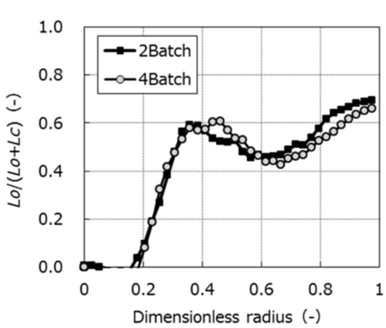

Fig. 8 Distribution of layer thickness ratio in radius at furnace throat

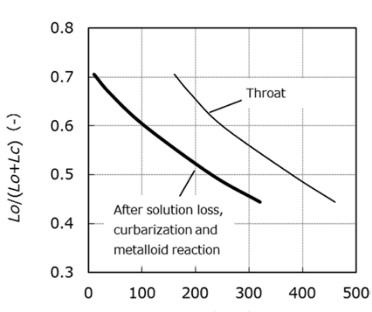

Fig. 9 Coke rate (CR) supplied to the raceway corresponding to layer thickness ratio in radius of furnace throat

3.3 Effects on raceway of blast condition and rate of coke supplied to lower furnace part

The ratio between the total cross-sectional area of the blast furnace tuyere raceways and the cross-sectional area of the furnace floor at the same height level (hereinafter referred to as "raceway area ratio" [9]) affects the reductant rate of the blast furnace as follows: In short, the increase in the raceway area ratio is due to the increase in blast energy and increases the inflow of gas to the center. This suppresses the peripheral gas flow, decreases the heat dissipated form the furnace body, and decreases the reductant rate. On the other hand, an excessive increase in the raceway area ratio accompanied a decrease in the deadman coke volume, which decreases the heat capacity of the furnace and conversely increases the reductant rate. The Kobe No. 3 blast furnace is a small blast furnace with a relatively large raceway area ratio. It therefore

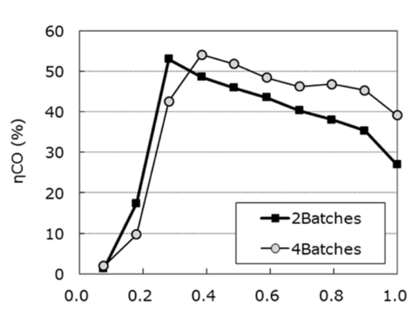

Fig.10 Radial distribution changes of gas utilization ratio at furnace throat in low coke rate operation

Table 2 Changes of raceway area ratio and reducing agent rate

		Before (2016/4)	After (2016/10)	dif.
Productivity	(t/d/m^3)	1.92	1.99	+0.07
Blast volume	(Nm^3/min)	2854	2601	-253
Oxygen	(Nm^3/min)	105	160	+55
CR	(kg/ t)	315	283	-32
PCR	(kg/ t)	198	220	+22
Raceway area ratio	-	0.514	0.498	-0.016
RAR	(kg/ t)	513	503	-10

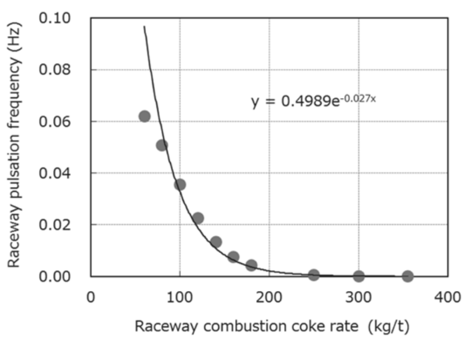

Fig.11 Relationship between combustion coke rate at tuyere and pulsation frequency of raceway

has a margin to decrease the raceway area by high oxygen enrichment, and the pressure loss in the furnace can be decreased as the amount of gas in the furnace decreases. In this low coke rate operation, the raceway area ratio of the Kobe No. 3 blast furnace was decreased from 0.514 (average value in April 2016) to 0.498 (average value in October 2016), resulting in a decrease in the reductant rate from 513 kg/tonne to 503 kg/tonne (**Table 2**).

Fig.11 shows the relationship between the combustion coke rate at a tuyere and the pulsation frequency[10] of its raceway. An increase in the pulsation frequency of a raceway means that bridging is likely to occur immediately above the tuyere, and the occurrence of bridging increases the risk of tuyere breakage due to the fall of unreduced FeO. In Fig.11, the pulsation frequency of the raceway increases as the combustion coke rate at the tuyere decreases. This is because the amount of coke supplied to the lower furnace part decreases due to the decrease in the combustion coke rate at a tuyere, turning smoothly moving layers into almost stationary layers. In particular, when the combustion coke rate at a tuyere falls below 100 kg/tonne, the pulsation frequency of the raceway increases rapidly. Assuming that the amount of carbon consumed due to solution loss is 90 kg/tonne, the amount due to metalloid reaction is 5 kg/tonne, and the amount due to carburization is 50 kg/tonne, the lower limit of the coke rate charged from the furnace top is calculated to be approximately 245 kg/tonne. This value was used as the guideline for the lower limit in low coke rate operation.

4. Results of low coke rate operation of Kobe No. 3 blast furnace

Fig.12 shows the change in operational data associated with the low coke rate operation. High oxygen enrichment operation (from 2.8% to 4.6%) began in April 2016, and the amount of high calorie coal was increased (from 60% to 100%) along with the increase of pellets (from 65% to 80%) on August 5. On this occasion, a complex control of burden distribution and pulverized coal injection began, decreasing the coke rate from 315 kg/tonne to 283 kg/tonne. It should be noted that the low coke rate operation was not performed from September 19th to October 17th.

In addition, η CO increased with an increasing addition of pellets, and the effect of self-fluxed dolomite pellets with excellent high temperature melt down properties was fully exploited. At the same time, Si in the molten iron was also decreased (from 0.71% to 0.48%).

Fig.13 shows the change in the temperature distribution inside the furnace measured by a descending probe[11] during low coke rate operation. Focusing on the 1,200℃ line, which corresponds to the upper surface of the softened cohesive zone, the 1,200℃ line was kept under control almost at the upper end of the furnace bosh despite a decrease in coke rate (from 315 kg/tonne to 283 kg/tonne). This verifies that the heat flow rate at the lower furnace part is controlled properly by the complex control of the burden distribution and pulverized coal injection. Incidentally, on the basis of the fact that a decrease in hot metal Si (from 0.71% to 0.48%) was observed with the decrease in molten-iron temperature (from 1,507℃ to 1,498℃), the decrease in hot metal Si after correcting the molten iron temperature is estimated to be 0.71% to 0.54%.[12] From this result, it is considered that the increase in self-fluxed dolomite pellets lowered the lower surface level of the cohesive zone (1,450℃) while maintaining the 1,200℃ line at the upper end of the furnace bosh.

Table 3 shows the results of low coke rate operation for the Kobe No. 3 blast furnace. In this trial, the coke rate reduction effect (from 315 kg/tonnes to 283 kg/tonnes) brought about by increasing the self-fluxed dolomite pellets was 19 kg/tonnes, and the effects of complex controlling of the oxygen enrichment rate and increasing the amount of high calorie (low VM) coal were 8 kg/tonne and 4 kg/tonne, respectively. Including other considerations, the coke rate was successfully decreased to 32 kg/tonne in total.

Table 4 compares the specifications of blast

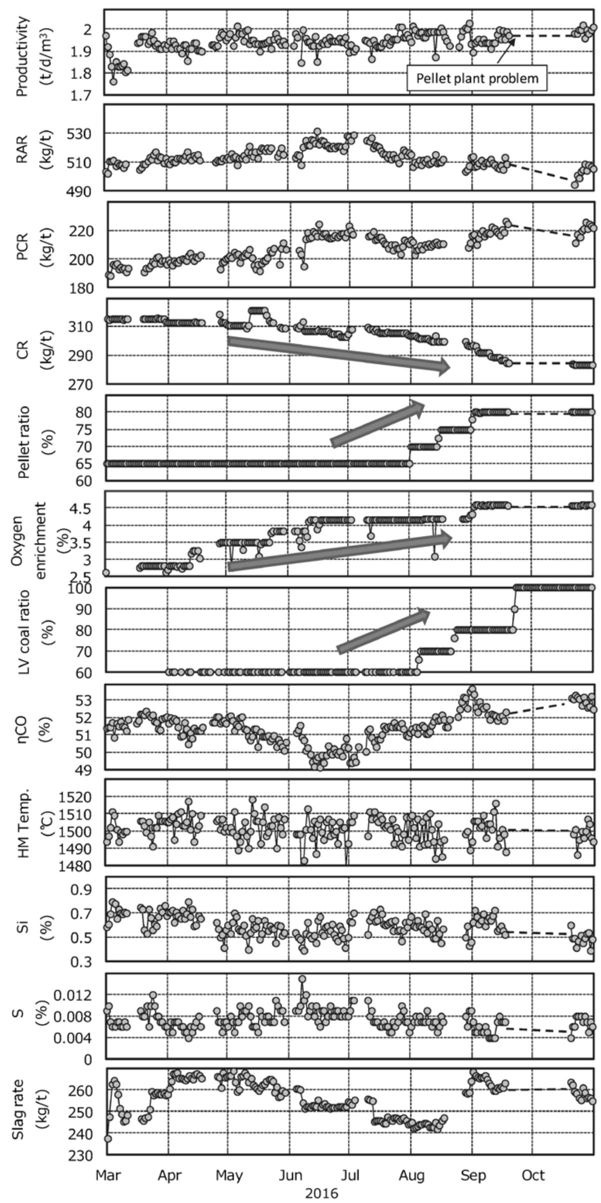

Fig.12 Changes of operation data with low coke rate operation

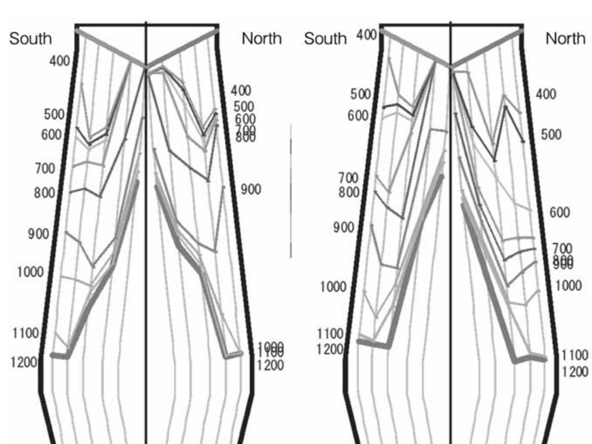

Fig.13 Changes of temperature distribution of blast furnace with low coke rate operation

Table 3 Results of low coke rate operation

		Before (2016/4)	After (2016/10)	dif.	
Productivity	(t/d/m^3)	1.92	1.99	+0.07	
RAR	(kg/ t)	513	503	-10	
CR	(kg/ t)	315	283	-32	
PCR	(kg/ t)	198	220	+22	
		Before (2016/4)	After (2016/10)	dif.	⊿CR (kg/t)
Pellet rate	(%)	65	80	+15	-19
Oxygen enrichment	(%)	2.8	4.6	+1.8	-8
LV coal rate	(%)	60	100	+40	-4
Converter slag rate	(kg/t)	5	10	+5	-3
Other	(-)	-	-	-	2
SUM.	(-)	-	-	-	-32

Table 4 Comparison of blast furnaces in low coke rate operation

		2016/4	2016/10	2009/9-10
		Kobe 3BF		IJmuiden 7BF
Inner volume	m^3	2112		-
Working volume	m^3	1863		3775
Productivity	t/d/m^3	1.92	1.99	2.22
Pellet ratio	%	65	80	60
Sinter ratio	%	0	0	40
Lump ore ratio	%	35	20	0
RAR	kg/t	513	503	495
CR	kg/t	315	283	261
PCR	kg/t	198	220	234
Heat flux ratio	-	0.81	0.83	-
O_2 enrichment	%	2.8	4.6	-
ηCO	%	51.5	52.9	49.4
Slag rate	kg/t	258	257	195

furnaces. Outside Japan, Tata Steel Limited achieved a low coke rate operation of 261 kg/tonne at its IJmuiden 7BF.[13] It is noteworthy that IJmuiden7BF has realized low slag rate operation despite the operating conditions of the mixed charging of pellet and sintered ore.

On the other hand, the Kobe No. 3 blast furnace has the slag rate almost leveling out (258 kg/tonne to 257 kg/tonne) despite the increase in pellets (from 65% to 80%). This is due to the increase and fluctuation of the gangue (SiO_2, Al_2O_3) rate in the raw material ore of pellets, that is, the deterioration of the iron ore raw material that is occurring in Japan's ironmaking industry.[14] This is also attributable to the low and stable S in molten iron required from the steelmaking process, that is, to achieve high quality steel.

5. Summary of low coke rate operation

In the Kobe No. 3 blast furnace, Japan's only all-pellet operation was continued, lump ore was replaced with self-fluxed dolomite pellets, and the complex control of burden distribution and pulverized coal combustion was optimized. As a result, low coke rate operation at 283 kg/tonnes was achieved under the harsh conditions of 80% pellet composition and all raw materials being stored in a yard. The results are summarized below:

(1) In small blast furnaces, the control of the melt

down properties at high temperatures of the periphery ore is of particular importance. In this all-pellet, low coke rate operation (283 kg/tonne), lump ore was replaced with self-fluxed dolomite pellets, and the upper surface of the softening cohesive zone (1,200 ℃ line) was successfully controlled almost at the upper end of the furnace bosh. This result is presumably because the heat flow rate at the lower furnace part was properly controlled by the complex control.

(2) A decrease in hot metal Si (from 0.71% to 0.48%) was observed, indicating that the lower level of the cohesive zone was successfully lowered by increasing the self-fluxed dolomite pellets.

(3) The increased addition of pellets increased η CO, indicating that the effect of self-fluxed dolomite pellets was fully exploited.

Conclusions

The blast furnace operation at Kobe Works of Kobe Steel closed its long history on October 31, 2017. Meanwhile, after the consolidation of the upstream process equipment into Kakogawa Works of Kobe Steel, stable operation of the two large blast furnaces and low coke rate operation have become even more important.

In the future, the ironmaking industry in Japan will be required to produce higher quality steel using iron ore with deteriorating quality. Kobe Steel strives to improve the operation of the large blast furnace at Kakogawa Works by effectively utilizing the technologies of burden distribution control in accordance with high pellet composition, and high temperature melt down control of self-fluxed dolomite pellets, as described in this paper.

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