

Application of High Ratio Coke Mixed Charging Technique to Blast Furnace[†]

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Abstract:

Technique for high-ratio coke-mixed-charging was developed and applied at No. 6 blast furnace in JFE Steel's East Japan Works (Chiba District) as the first case of application to a large blast furnace. Simultaneous discharging of ore and coke from the top bunkers, and the precise control of burden distribution technique with the mathematical model considering the segregation behavior of mixed layer have made it possible. Also, FCG(Flow Control Gate)-Dynamic charging method improved ratio of uniformly mixed coke. Since April 2002, high productivity and low RAR operation with the world's lowest level of sinter ratio has been conducted using high-ratio coke-mixed-charging technique.

1. Introduction

Under conditions which include global warming and rapidly rising raw material prices, further promotion of low reducing agent ratio (RAR), low coke ratio operation, and an expansion of the degree of freedom in raw material selection by increasing the use ratio of low grade raw materials are important technical issues of blast furnace operation in the future.

Ore-coke mixed charging, in which coke is mixed in the sinter or iron ore raw material and charged into the blast furnace, is known as one technique for achieving these objectives^{1,2)}. Although this is a technique which improves the permeability and reducibility of the softening and cohesive zone, for various reasons, the mixing ratio in actual furnaces is limited to around 5 wt%. These include the fact that the difference in the sizes of the raw material and coke causes deterioration

of permeability in the lumpy zone, O/C control in the furnace radial direction is difficult due to segregation of the mixed layer and, as a result, the targeted burden distribution is not achieved, and the segregated mixed coke flows in toward the center of the burden layer surface, where it is degraded by the gasification reaction, and then accumulates in the deadman, causing deterioration of gas and liquid permeability in the furnace bottom, among other problems. Moreover, because it is necessary to mix ordinary lump coke if the coke mixing ratio is increased, the coke/raw material size ratio increases rapidly, and segregation of the mixed layer becomes extremely remarkable.

JFE Steel investigated the characteristics of the ore-coke mixed layer and established a high ratio coke mixed charging technique for ore raw material at East Japan Works (Chiba District) by developing a uniform charging method. As a result, high productivity operation was achieved under ultra-low sinter ratio conditions.

2. Evaluation of Ore-Coke Mixed Charging

2.1 High Temperature Properties of Ore-Coke Mixed Layer

2.1.1 Under-load-reduction experiment

The effects of coke mixing on the high temperature properties of ore were investigated in an under-load-reduction experiment. The crucible itself and the top and bottom plates were made of carbon. The structure of the apparatus made it possible to apply a load to the sample

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in the crucible by passing a carbon rod from a moving weight-type load generating device at the furnace top. The heating temperature, composition of the introduced gas, and load were controlled automatically by a program.

The sample material was filled in a carbon crucible with an inner diameter of 100 mm so that a mixed layer of raw material and coke was introduced in the soaking zone (height: approximately 100 mm) between layers of coke with a particle size of 15–25 mm. The amount of ore was held constant at 900 g, and the amount of coke was changed corresponding to the mixing ratio.

In the raw materials used, the ratio of sinter was varied to 100, 75, and 65 wt%, and the balance was lump iron ore. The sizes of the sinter and lump ore were adjusted to 10–15 mm, and that of the mixed coke was adjusted to either 10–15 mm or 30–40 mm. The coke and mixture of sinter and lump ore were charged into the crucible one piece at a time using tweezers so as to obtain a substantially homogeneous distribution in the crucible.

2.1.2 Results of under-load-reduction experiment

The effects of the mixed coke ratio and sinter ratio on maximum pressure drop in the under-load-reduction experiment are shown in **Fig. 1**. The maximum pressure drop was greatly reduced by coke mixing, and decreased with all sinter ratios up to a coke mixing ratio of 12.5 wt%. At a 15 wt% coke mixing ratio, the maximum pressure drop showed substantially the same value or a slight increase.

Figure 2 shows the change in reducibility at 1 473 K. Although the deviations in the data are comparatively large, reducibility increased with the coke mixing ratio up to a mixing ratio on the 10 wt% level.

Next, the effect of the coke mixing ratio and mixed coke size on maximum pressure drop with a sinter ratio of 75 wt% is shown in **Fig. 3**, and similarly, the effect on the relationship with reducibility at 1 473 K is shown in **Fig. 4**. When the size of the mixed coke is increased, the permeability improvement decreases somewhat, but the fact that permeability improves remarkably as the coke

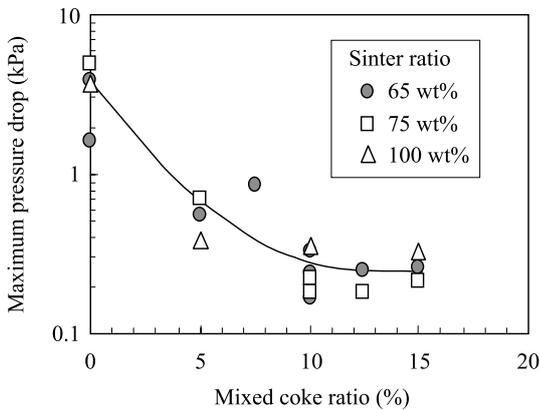


Fig. 1 Effects of mixed coke ratio and sinter ratio on high temperature gas permeability of burden material

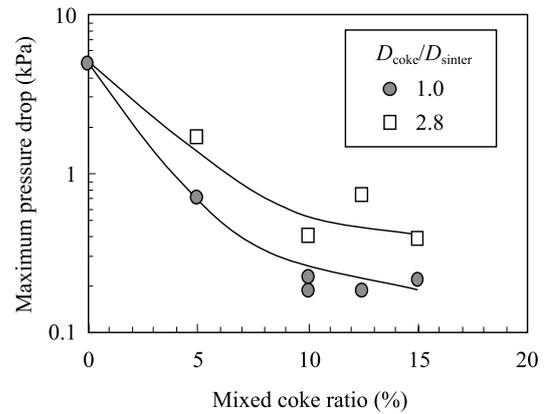


Fig. 3 Change in the maximum pressure drop with large-diameter mixed coke with a sinter ratio of 75 wt%

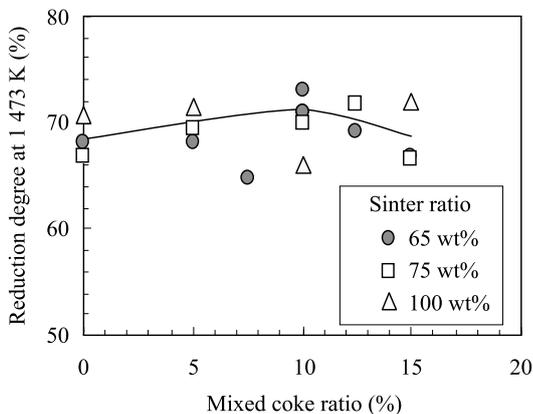


Fig. 2 Effects of mixed coke ratio and sinter ratio on reduction degree at 1 473 K

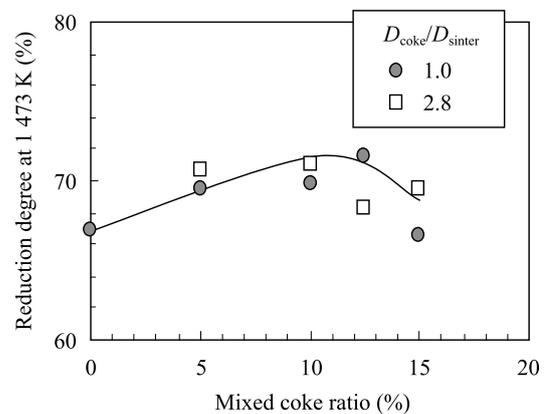


Fig. 4 Change in the reduction rate at 1 473 K with large-diameter mixed coke with a sinter ratio of 75 wt%

mixing ratio increases shows the same tendency as with small coke. It was found that the size ratio has virtually small effect on reducibility.

From the results of observation of the cross section of samples extracted after interrupting the under-load-reduction experiment, voids were observed at the boundary between the softened raw material and the mixed coke. It is assumed that this was due to local carburization resulting from contact between the reduced and metalized sinter and coke, and melting of the metal in the boundary area, which generated the voids³⁾. In other words, it is considered that permeability was secured by the flow of gas in these voids at high temperature, as a result of mixing of coke in the raw material. The reducibility of raw materials with low reducibility, such as lump ore, is presumably improved under a low sinter ratio condition because mixing of coke suppresses the formation of unreduced FeO and promotes reduction of the lump ore.

Based on the experimental results described above, with uniform mixing, it was found that the high temperature properties of the raw material layer are improved by coke mixing ratios up to 10 wt%, even when using a lump coke mixture.

2.2 Effect of High Ratio Coke Mixed Charging on Blast Furnace Operation

2.2.1 Effect on permeability of cohesive zone

If high ratio coke mixed charge is performed in an actual blast furnace, there is concern that the thickness of the coke layer (coke slit) charged between the raw material layers may decrease, deteriorating gas permeability, particularly in the cohesive zone.

On the other hand, the under-load-reduction experiment proved that the permeability of the softening and cohesive zone is remarkably improved by coke mixing, as discussed in paragraph 2.1.

Based on this, mixed charging is expected to reduce the permeability resistance of the whole cohesive zone as a result of the increase in the amount of gas passing through the cohesive layer in spite of the decrease in the amount of gas passing through the coke slit.

Therefore, permeability in the cohesive zone was evaluated considering these effects.

It was assumed that the respective gas distributions in the cohesive layer and the coke layer are determined as the radial pressure loss in the two layers becomes the same. The permeability resistance of the cohesive layer was calculated using the equation proposed by Sugiyama et al.⁴⁾, as shown in Eq. (1), and that of the coke layer was calculated using Ergun's formula⁵⁾, which is shown as Eq. (2).

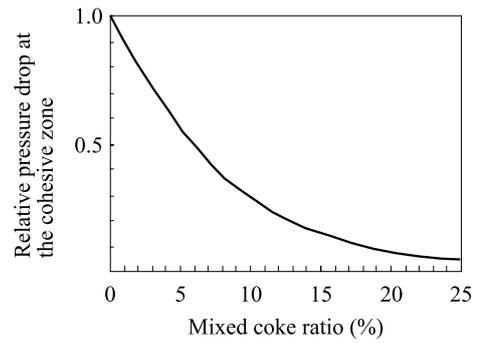


Fig. 5 Calculation result of change in pressure drop at the cohesive zone by coke mixing

$$\frac{\Delta P}{L} = \left[\frac{1}{Cm} \right]^2 \left[\frac{1}{\Phi D_p (1 - S_r)} \right] \left[\frac{\rho_g u^2}{g D_p} \right] \dots \dots \dots (1)$$

$$\frac{\Delta P}{L} = 150 \frac{u\mu}{g D_p^2} \frac{(1 - \epsilon)^2}{\epsilon^3} + 1.75 \frac{\rho_g u^2}{g D_p} \frac{1 - \epsilon}{\epsilon^3} \dots \dots \dots (2)$$

where, ΔP : differential gas pressure, L : distance, C : discharge coefficient, m : opening ratio, Φ : shape factor of particles in mixed layer, D_p : average size of particles, S_r : contraction of mixed packed bed, ρ_g : density of gas, u : superficial velocity of gas, g : acceleration of gravity, M : coke mixing ratio, and ϵ : void ratio of packed bed. The values of D_p and Φ were obtained by observation of the cross sections of the samples in the interrupted tests in the under-load-reduction experiment.

The value of S_r was given by Eq. (3) based on the effect of the coke mixing ratio and the size ratio of the mixed coke and sinter which was obtained in the under-load-reduction experiment on the contraction of the mixed packed layer at 1 573 K. The value of ϵ was given as a function of the mixing ratio from the measured results of the permeability of the packed layer.

$$S_r = -1.88M + 61.3 \dots \dots \dots (3)$$

The number of cohesive layers in the cohesive zone was estimated based on a cone having the diameter of the furnace belly as its base and the distance from the root to the top as its height. The profile of the cohesive zone was obtained from the results of a 2-dimensional blast furnace simulator under a base condition in which coke mixing is not applied.

The results obtained by this calculation are shown in Fig. 5. Based on these results, it was assumed that the permeability of the cohesive zone as a whole increases as the coke mixing ratio increases.

2.2.2 Changes in blast furnace operation due to high ratio coke mixed charging

From the results of the experiment described

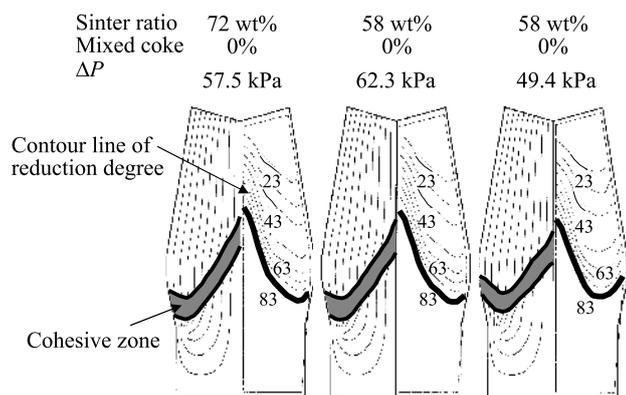


Fig. 6 2-D blast furnace simulation model calculation: Change in cohesive zone and reduction degree in the blast furnace by the sinter ratio and coke mixing

above, the changes in blast furnace operation when the sinter ratio is changed were predicted using the 2-dimensional simulator. The effects of the sinter ratio and the coke mixed charging ratio were investigated for base operational parameters (productivity: 2.0 t-pig/m³·d, coke ratio: 387.5 kg/t-pig, PCR: 89.1 kg/t-pig, blast rate: 7 780 Nm³/min, oxygen enrichment ratio: 1.4%).

The calculated results are shown in **Fig. 6**. If the sinter ratio is reduced from 72 wt% to 58 wt%, reduction is delayed and pressure drop increases due to swelling of the intermediate cohesive zone. However, mixing of coke at a ratio of 120 kg/t-pig had the effect of increasing the reducibility in the furnace. Although coke mixed charging increases the contraction starting temperature and meltdown starting temperature, the permeability of the cohesive layers is improved, and the width of the cohesive zone is reduced and the zone shifts upward due to a decrease in contraction. As a result of these changes, coke mixing has the effect of reducing furnace pressure drop, even with a low sinter ratio.

3. High Ratio Coke Mixed Charging Technique

3.1 Blast Furnace Charging Model Experiment

3.1.1 Experimental method

The key points for applying high ratio coke mixed charging to the actual blast furnace are to set the timing of mixing as close to the blast furnace as possible, and to realize advanced control of the charging method so as to achieve the preset mixing ratio based on prediction of the segregation of the mixed layer at the furnace top burden layer surface. To achieve this, the changes over time in the coke mixing ratio during discharge from the vertical chute and segregation of the mixed layer at the burden surface were investigated in model charging

experiments, and a charging method for the actual blast furnace was designed by incorporating the results in a burden distribution model.

The charging model used in this experiment was a 1/17.8 scale charging model of No. 6 BF at East Japan Works (Chiba District). Number 6 BF is a bell-less type blast furnace which is equipped with 3 parallel bunkers at the furnace top. In order to reproduce the raw material discharge behavior in the actual furnace, the charging model includes charging equipment comprising bins, surge hoppers, and a bell-less charging device. During the charging experiment, air is blown at 200 Nm³/h from gas blowing ports at the furnace bottom.

The effects of the charging rate and size ratio of the mixed coke and raw material on the segregation behavior of the mixed layer at a burden surface with a 30° slope were investigated. As the method of mixing the coke and raw material, based on model experiments, simultaneous discharge from the furnace top bunkers was adopted (raw material and coke were discharged from the respective bunkers and mixed on the rotating chute), in which the change over time in the coke mixing ratio during discharge from the vertical chute is constant. Charging was performed in a single ring with the tilting angle of the rotating chute set to 30°, 40°, 48°, and 54.5°.

The furnace top burden profile after charging was measured using a laser displacement meter. Specimens were sampled by inserting a round tube into the burden surface in the radial direction, and the distribution of the coke mixing ratio was obtained at various radial positions. The sampled specimens were separated into raw material and coke by gravity separation using a saturated aqueous solution of sodium iodide.

3.1.2 Quantification of segregation behavior of coke and ore at burden surface

The radial distribution of the coke mixing ratio at the burden surface in single ring charging with a rotating

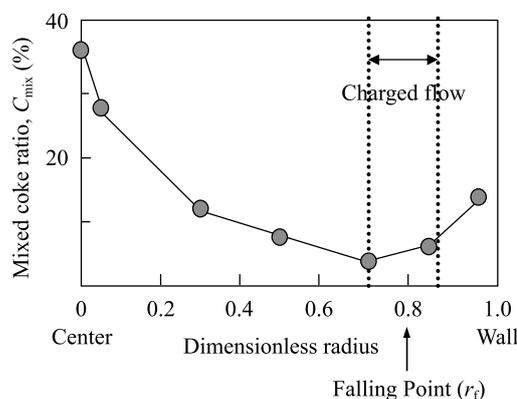


Fig. 7 Radial distribution of the mixed coke ratio in the burden (Single-ring discharge, chute tilting angle 54.5°)

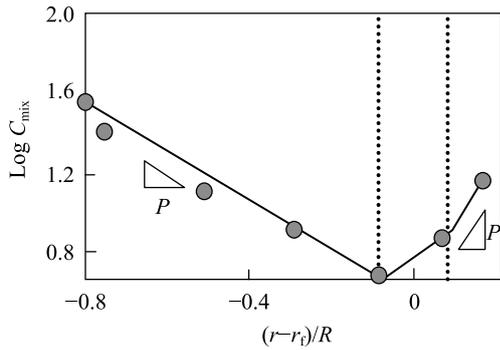


Fig. 8 Arranged result using Eq. (5) of Fig. 7

chute tilting angle of 54.5° is shown in Fig. 7. It can be understood that the coke mixing ratio increases with distance from around the mainstream falling point toward the furnace center and the furnace wall.

If a group of particles having a size distribution flows on a sloping surface, percolation occurs, in which the coarse grains tend to segregate toward the lower end of the slope, while the fine grains remain at the upper end. According to Miwa, percolation on a sloping surface has been formulated as shown in Eq. (4) as a function of the distance L which the particles flow⁶.

$$\log y = aL + b \dots\dots\dots(4)$$

where, X is the percentage of coarse grains. It is known that a mixture of two types of grains with different densities shows similar segregation behavior when flowing on a sloping surface⁷. As it is also considered possible to apply this fact to the segregation behavior of a mixed layer of coke and ore, the experimental results were arranged using the following equation.

$$\log \left(\frac{X}{1-X} \right) = P \left(\frac{r-r_f}{R} + w \right) + C \dots\dots\dots(5)$$

where, X : coke mixing ratio, r_f : distance between the center and falling point, R : radius of the furnace mouth, w : dimensionless falling flow width, and C : logarithm of the coke mixing ratio at the falling point. P shows the tendency of segregation of the mixed layer, and will be referred to in this paper as the “percolation constant.” As a result of various experiments, w and C shows basically constant values in all cases, these being 0.1 and 1.2, respectively.

When the above Fig. 7 was converted using Eq. (5), the results show a linear relationship in the respective regions, as shown in Fig. 8. Based on this, it was found that the segregation behavior of the mixed layer at the burden surface can be formulated by Eq. (5). The percolation constant P decreased as the charging rate

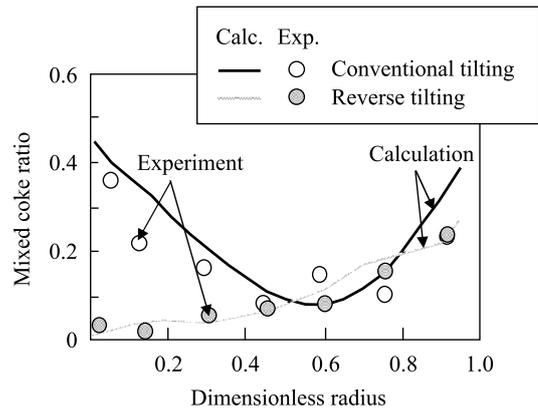


Fig. 9 Comparison of the calculated and the experimental results for conventional tilting and reverse tilting

increased or the size ratio decreased.

3.2 Application of High Ratio Coke Mixed Charging to Actual Blast Furnace

3.2.1 Burden distribution model for mixed charging

A numerical model of burden distribution which considers the segregation behavior of the mixed layer was constructed. The percolation constant obtained from the experimental results described above was given as a function of the size ratio and charging rate, and was incorporated in the conventional burden distribution model by the following procedure.

- (1) Calculation of the coke mixing ratio in each rotation
- (2) Calculation of the mainstream falling track
- (3) Calculation of the radial distribution of the mixed coke
- (4) Calculation of the burden profile
- (5) Calculation of the coke mixing ratio in the radial direction

In order to verify the accuracy of the obtained model, the calculated results were compared with the results of model experiments for cases of charging with the conventional tilting and a reverse tilting. The results showed good agreement between the calculated results and the experimental results, as shown in Fig. 9. Thus, it was found that prediction and control of the burden distribution considering the mixed layer is possible using this model.

3.2.2 High ratio coke mixed charging technique for uniform coke mixing ratio

Using the burden distribution model described in the previous section, a high ratio coke mixed charging technique which results in a uniform coke mixing ratio was studied. The coke and ore were divided into two batches each. Lump coke was mixed in the 1st batch, and small coke was mixed in the 2nd batch. The lump

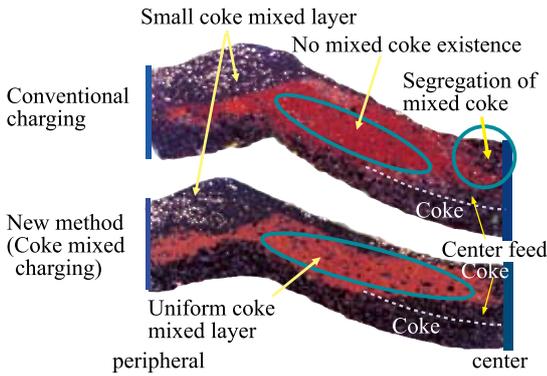


Fig. 10 Comparison of mixed coke distribution of high ratio coke mixed charging by the conventional method and the developed method (Cross-section of burden model experiments)

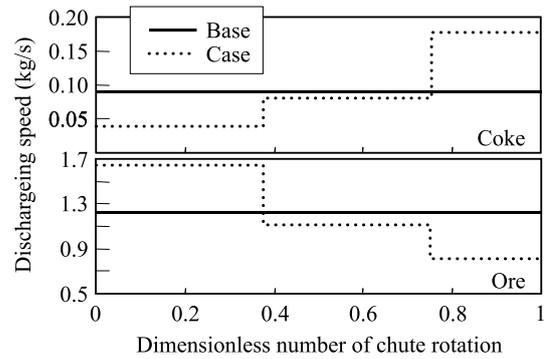
coke was charged simultaneously from a top bunker, and the small coke was mixed with the ore by simultaneous discharge from a bin. The coke mixing ratio was 3.75 wt% in both batches, resulting in a total of 7.5 wt%.

Using the burden distribution model, the charging pattern was set so as to obtain a uniform mixing ratio in the radial direction, and the effect was confirmed by performing a charging experiment. In order to observe the burden cross section, after the charging experiment, a low viscosity resin was poured on the burden surface and allowed to soak into the burden, and a section of the burden was cut after the resin had hardened. The results of mixed charging with the conventional charging pattern and the charging pattern in this experiment are shown in Fig. 10. In both cases, the small coke was distributed uniformly on the coke terrace in the 2nd batch of ore. On the other hand, with the conventional method, the lump coke mixed in the 1st batch segregated and flowed to the center, whereas with the new pattern, the lump coke was uniformly distributed in the ore.

3.2.3 Improvement of mixing by FCG dynamic control

In order to minimize the effect of segregation of the mixed layer at the burden surface, the discharge rates of raw material and coke from the bunkers were changed over time. Concretely, the opening of the flow control gates (FCG) was controlled independently so that coke discharge was gradually increased and raw material discharge was gradually decreased during reverse tilting.

In this experiment, the charging model device described previously was used. As combinations of FCG opening patterns, 3 cases were compared, these being case 1, in which only the coke FCG was opened in steps, case 2, in which only the raw material FCG was closed in steps, and case 3, in which the raw material FCG was closed simultaneously with opening of the coke FCG (Fig. 11). After this experiment, the cross sections of the



	FCG pattern		Mixed coke ratio (%)
	Coke	Ore	
Base	Base	Base	66.7
Case 1	Case	Base	73.9
Case 2	Base	Case	76.4
Case 3	Case	Case	76.8

Fig. 11 Pattern of FCG-Dynamic charging

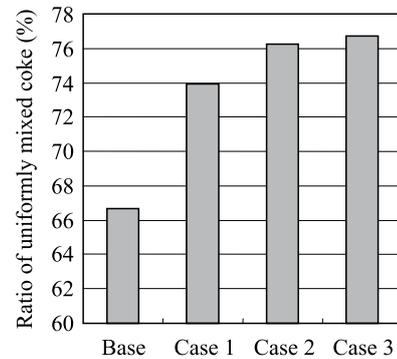


Fig. 12 Change in uniformly mixed coke ratio by FCG-Dynamic charging

burden surface were observed, the mixed coke yield in the ore layer was obtained by image analysis, and the uniformly mixed coke ratio was obtained.

The results are shown in Fig. 12. The coke mixing ratio improved approximately 8–10% with FCG dynamic control, and in particular, mixing improved greatly in case 3. This is considered to be because the amount of coke flowing to the furnace center was reduced by initially charging with a low mixed coke ratio and increasing the mixed coke ratio in charging at the periphery.

3.3 Low Sinter Ratio, High Productivity Operation at Chiba No. 6 BF by High Ratio Coke Mixed Charging

High ratio coke mixed charging was begun at Chiba No. 6 BF on April 3, 2002. Using 4 batch charging (coke and raw material in two batches each) as a base condition, in O1, 75 kg/t-pig was mixed by simultaneous discharge from the top bunker, and in O2, 45 kg/t-pig was mixed by discharging small coke from a bin.

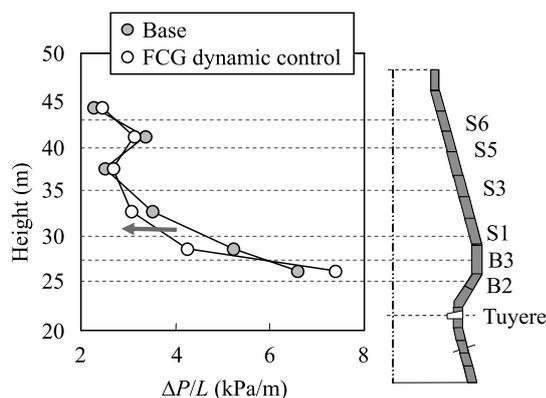


Fig. 13 Pressure drop distribution obtained by shaft pressure gauge before and after FCG dynamic control at Chiba No.6 BF

Immediately after the changeover to high ratio coke mixed charging, collapse of the burden surface during charging and unstable permeability due to thinning of the coke layer around the center of the furnace were observed. However, following adjustments in the charging pattern, the furnace condition stabilized and η_{CO} also increased. In particular, permeability resistance was greatly improved at the bottom of the shaft and below.

The results of an analysis of the operating data before and after the start of high ratio coke mixed charging showed that shaft efficiency improved as a result of high ratio coke mixed charging, and the reducing agent ratio (RAR) was reduced by approximately 10 kg/t-pig at a coke mixing ratio of 6.2 wt%. The improvement in shaft efficiency and reduction of RAR are considered to be due to improvement of permeability and reducibility in the cohesive zone, reduction of the temperature of the thermal reserve zone, and other related factors. The Si concentration in the hot metal decreased by approximately 0.15 wt%, this is attributed to an increase in the meltdown starting temperature with coke mixed charging, which resulted in a lowering of the level of the cohesive zone.

Figure 13 shows the change in the distribution of permeability resistance in the blast furnace height direc-

tion before and after application of FCG dynamic control. The mixed coke ratio was 120 kg/t. During charging, the opening of the coke FCG was doubled, while the opening of the raw material FCG was held constant. From this, it can be understood that the permeability resistance at the bottom of the shaft was greatly reduced. In addition, shaft efficiency was also improved.

As described above, blast furnace operation was greatly improved by high ratio coke mixed charging, and it is clear that low RAR, high productivity operation with a low sinter ratio is possible using this technique.

In application of the new technique to actual operation of No. 6 BF at East Japan Works (Chiba District), the raw material specification was reduced while holding the operating parameters during operation of No. 5 BF basically constant. The sinter ratio of 72 wt% was gradually reduced beginning in November 2002, and in March 2003, a monthly average sinter ratio of 56 wt% was achieved (productivity: 2.0 t/m³/d, RAR: approximately 500 kg/t-pig).

4. Conclusion

High ratio coke mixed charging was applied in commercial operation of a large-scale blast furnace for the first time in the world, realizing ultra-low sinter ratio operation/high productivity operation. Since No. 5 BF at East Japan Works (Chiba District) was blown off in June 2004, No. 6 BF has continued in extremely stable operation.

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