Development of FCG Dynamic Control Technique at Mixed Charging of Massive Coke into Ore Layer

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A controlling method of the radial mixed coke ratio distribution under high coke mixed charging, which is called FCG (Flow Control Gate) dynamic control method was studied with the aim of stable operation with high productivity and low RAR at Chiba No. 6 blast furnace. For this purpose, scale model experiments and mathematical burden distribution model calculations were performed. The effects of FCG dynamic control with ore and coke simultaneous discharging from the respective top bunkers on the mixed coke ratio distribution were examined and applied to Chiba No. 6 blast furnace. After application of FCG dynamic control, improvements of gas utilization efficiency: +0.2%, gas permeability at cohesive zone (the part of lower shaft): –14.7% and coke ratio: –4.2 kg/t (with constant RAR) were confirmed. Since June 2007, high productivity operation with low RAR has been conducted at Chiba No. 6 blast furnace.

KEY WORDS: blast furnace; CO₂ emission; low RAR operation; bell-less charging; coke mixed charging; coke mixed ratio; coke mixing method; simultaneous discharging; burden distribution; permeability; cohesive zone.

1. Introduction

Low RAR (reducing agent rate) operation of blast furnaces is indispensable for reducing CO₂ emissions. In low RAR operation, it is important to maintain good gas permeability in the cohesive zone, which is the area of highest gas resistance in the blast furnace. Past measures to improve the permeability of the cohesive zone are, improvement of the high temperature properties of sinter and coke, particle size distributions of sinter and coke, radial burden distribution control, and coke and ore mixed charging. Coke mixed charging decreases ore shrinkage and protects the coke from the sol-loss reaction, thereby increasing the void fraction in the cohesive zone and improving gas permeability and reducibility. Coke mixed charging was applied to JFE Steel’s Chiba No. 6 blast furnace, which has a bell-less type charging system with three parallel top bunkers. Segregation in the mixed layer during charging through the rotating chute and at the burden surface are problems with this method. Segregation is caused by differences in the diameter and/or density of the ore and coke, the burden surface and the inclination angle of burden surface. When the coke mixing ratio exceeds the amount of under-size coke (small coke), lump coke is also mixed, and segregation in the mixed layer becomes remarkable. To prevent segregation even in this case, a coke-ore simultaneous discharge method, in which ore and coke are discharged from the respective top bunkers and mixed on the charging chute, and the reverse tilting charging method, that is, charging from the furnace center to the periphery, are applied to Chiba No. 6 blast furnace. Since April 2002, high productivity and low RAR operation has been conducted stably with 120 kg/t coke mixing charging into ore layer. But, there is still room for improvement in segregation of the mixed layer for improving gas permeability and less RAR operation within a coke-ore simultaneous discharge method. Therefore, a newly mixed coke ratio control method, which is called FCG (Flow Control Gate) dynamic control, was studied by a mathematical model calculation and scale model experiment. As a result, the authors developed a new technique for high coke mixed charging and applied this method at JFE Steel’s East Japan Works (Chiba District) No. 6 blast furnace.

2. Scale Model Experiment

2.1. Experimental Procedure

The experimental apparatus is a 1/17.8 scale model of Chiba No. 6 blast furnace, which has a bell-less type charging system with three parallel top bunkers, as shown in Fig. 1. The scale model consists of ore bins, coke bins, a weighing hopper, and belt conveyers to recreate the charging system of the actual blast furnace. The furnace body has 12 holes in the lower part for air blowing during charging and an electromagnetic feeder to duplicate burden descent. While the materials are being charged, air is blown into the lower shaft to recreate the inclination of the burden surface. The experimental conditions and size of burden material were decided based on the scale factor of the experimental apparatus. In this experiment, sinter (which color is black), raw ore (red), coke (black) and color
sand as small coke (white) were used to distinguish the burden layer construction with observation of cross section. Particle size distributions of each material were shown in Fig. 2. The Froude number, which is the ratio of inertia to gravity was set for the dropping burden material and was matched with that of actual blast furnace.

2.2. Observation of Condition of Coke Mixture in Current Operation

2.2.1. Experimental Conditions

The condition of coke mixture in the ore layer was observed using the experimental apparatus shown in Fig. 1. The coke ratio was 400 kg/t. The charging weight and charging time of each batch were shown in Table 1. The charging sequence of Chiba No. 6 blast furnace is two coke batches (C1, C2) and two ore batches (O1, O2). The image of high ratio coke mixed charging method of Chiba No. 6 blast furnace comparison with conventional method is shown in Fig. 3. Lump coke was mixed into the first ore batch (O1) and small coke was mixed into the second batch (O2). Coke and ore were discharged from each top bunker simultaneously. Small coke was mixed on the ore belt conveyor. Raw ore was used as O1 and sinter was used as O2 to distinguish the mixed coke and ore. After charging, a low-viscosity liquid resin was poured from the surface into burden. After the resin solidified, a sample was cut off to observe the cross section of the burden.

2.2.2. Results of Observation of Cross Section

The results of high ratio coke mixed charging by the conventional method are shown in Fig. 4. Mixing of lump coke and small coke in the ore layer was substantially uniform, although some lump coke concentrated at the center. The concentrated lump coke is assumed to separate and flow to the center during charging. In addition, part of the O2 layer segregated to the burden surface at the center of the furnace.

2.2.3. Comparison of Mathematical Burden Distribution Model and Scale Model Experiment

An image analysis of Fig. 4 was done to quantify the condition of coke mixing in the ore layer. First, the burden was divided into the mesh shown in Fig. 5. The area ratios of coke and ore in each mesh were then calculated into binary data based on the difference of brightness of the coke and ore. The area ratios were integrated in a circumferential direction at each radial position to convert into volume of coke and ore. After the resin solidified, a sample was cut off to observe the cross section of the burden.

**Table 1.** Charging weight and charging time in this experiment.

<table>
<thead>
<tr>
<th></th>
<th>Charging weight (kg)</th>
<th>Charging time (sec)</th>
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<tbody>
<tr>
<td>C1</td>
<td>5.03</td>
<td>22.8</td>
</tr>
<tr>
<td>C2</td>
<td>2.01</td>
<td>22.8</td>
</tr>
<tr>
<td>O1</td>
<td>16.54</td>
<td>11.4</td>
</tr>
<tr>
<td>O2 + Small coke</td>
<td>14.59 + 1.44</td>
<td>11.4</td>
</tr>
</tbody>
</table>

**Fig. 1.** Experimental apparatus.

**Fig. 2.** Particle size distribution.

**Fig. 3.** The image of high ratio coke mixed charging method of Chiba No. 6 blast furnace.

**Fig. 4.** Cross-section of burden in scale model experiment (conventional method).
at each radial position.

**Figure 6** shows the radial distribution of the mixed coke ratio derived from the experiment (dots) in comparison with the calculated results by the mathematical burden distribution model (line).

The calculated and experimental results are in the same tendency. The increase in the mixed coke ratio at the center seems to be a result of the segregation of the lump coke, and that at the periphery is a result of small coke segregation in comparison with the observation result of cross section (Fig. 4). The decrease in the mixed coke ratio in the intermediate part is caused by segregation when the material flowed into the center. The target of mixed coke ratio distribution is uniform in a radial direction without segregation. The decrease in mixed coke flowing into the center not only leads to an increase in the mixed coke ratio in the intermediate part, but also prevents concentration of the reacted coke or coke fine in the deadman, which deteriorates gas and liquid permeability in the hearth. Moreover, if control of peripheral small coke is possible, a further increase in the mixed coke ratio in the intermediate part can be expected, resulting in improved gas permeability and gas utilization efficiency ($\eta_{CO} = CO_2/(CO+CO_2)$).

### 3. Effects of FCG Dynamic Control on Radial Mixed Coke Ratio Distribution

#### 3.1. Study Using the Mathematical Burden Distribution Model

Chiba No. 6 blast furnace is equipped with a variable FCG device. The charging speed from the top bunker into the furnace during one batch can be changed using the control gate opening ratio. **Figure 7** shows the concept of FCG dynamic control. In Fig. 7, X and Y show the number of chute rotations, and $\alpha$, $\beta$, and $\gamma$ show the charging speed. The charging speed is $\alpha$ from the beginning of charging to X, and can then be set to $\beta$ from X to Y, and finally set to $\gamma$ from Y to the finish of charging.

The effect of FCG dynamic control on the mixed coke ratio distribution was studied using the mathematical burden distribution model.

The calculation conditions are shown in **Fig. 8**. In Fig. 8, the ore and coke charging speeds are stepwise increase in Pattern 1, the ore and coke charging speeds are stepwise decrease in Pattern 2, respectively.

**Figure 9** shows the effects of the coke discharging speed on mixed coke ratio. FCG dynamic control was assumed to be only used for the coke bunker, while the ore charging speed was uniform. In case of simultaneous charging with reverse tilting, a stepwise increase of the coke discharging speed...
reduced the amount of coke that segregated and flowed into the center. Figure 10 shows the effects of the ore charging speed on the mixed coke ratio. A stepwise decrease of the ore discharging speed has the same effects.

3.2. Experimental Conditions
Based on the calculated results, a scale model experiment was conducted to study the effects of FCG dynamic control on the mixed coke ratio distribution. The experimental conditions are shown in Fig. 11. The charging speed converted to that of the commercial plant was calculated from the bulk density of the burden material used in the scale model experiment. The experimental conditions were the base condition and three cases, the base condition being uniform discharge of coke and ore. The FCG dynamic control used in this experiment for the three cases were: (Case 1) the coke discharging speed was gradually increased while the ore discharging speed was kept constant, (Case 2) the ore discharging speed was gradually decreased while the coke discharging speed was kept constant, and (Case 3) the coke discharging speed was gradually increased and simultaneously the ore discharging speed was gradually decreased. Average coke mixed ratio (= weight of coke/weight of ore) was 0.072. After charging, the respective cross sections of the burden were observed and image analysis was performed by the above-mentioned method.

3.3. Experimental Results and Discussion
A comparison of the results of observation of the cross sections is shown in Fig. 12 in the order of Base, Case 1, Case 2, and Case 3. In the base condition, a large amount segregated coke concentrated at the center, while mixture was insufficient at the periphery. The amount of segregated coke at the center decreased in Case 1, Case 2 and Case 3 compared with the base condition. A small amount of segregated coke was observed at the periphery in Cases 1 and 2, and mixture was insufficient at r/R=0.5, while in Case 3, the amount of segregated coke at the center was small, and coke mixing was almost uniform. Next, image analysis was performed by the method described above to quantify the condition of radial coke mixing.

Figure 13 shows the effects of FCG dynamic control on radial distribution of the mixed coke ratio. In the Base condition, the coke mixed ratio was large at the center and small at the periphery. On the contrary, the coke mixed ratio was small at the center and large at the periphery in Case 1.

<table>
<thead>
<tr>
<th>FCG pattern</th>
<th>Coke</th>
<th>Ore</th>
</tr>
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<tbody>
<tr>
<td>Base</td>
<td>Base</td>
<td>Base</td>
</tr>
<tr>
<td>Case 1</td>
<td>Case</td>
<td>Base</td>
</tr>
<tr>
<td>Case 2</td>
<td>Base</td>
<td>Case</td>
</tr>
<tr>
<td>Case 3</td>
<td>Case</td>
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</tbody>
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Fig. 10. Effect of ore charging speed on mixed coke ratio.

Fig. 11. Experimental conditions.

Fig. 12. Comparison of cross-sections.

Fig. 13. Effects of FCG dynamic control on radial distribution of the mixed coke ratio (image analysis).
Then, the fluctuation of radial distribution was large in Base and Case 1. The fluctuation of radial distribution were smaller in Case 2 and 3 compared with the base condition and Case 1, although mixed coke ratio was partially large at \( r/R = 0.72 \) in Case 2. In Case 3, mixed coke ratio was slightly large at the center and periphery, but coke mixed ratio was near the average at around \( r/R = 0.4 - 0.85 \). Figure 14 shows the effects of FCG dynamic control on standard deviation of radial coke mixed ratio. The smallest standard deviation was achieved in Case 3.

Figure 15 shows the effects of FCG dynamic control on mixed coke yield in the ore layer. The mixed coke yield was defined as the ratio of coke not segregated into the center or separated on the burden surface. In outer circumferential mesh of analytical region, if the area ratio of coke and ore exceed 0.8, then the coke in the mesh was regarded not mixed coke as segregated or separated coke, and excluded from mixed coke yield. In comparison with the base condition, the mixed coke yield in the ore layer improved by about 8% in Case 1, and by about 10% in Cases 2 and 3. Thus, the standard deviation of radial mixed coke ratio and mixed coke yield was improved by FCG dynamic control compared with the base condition (conventional).

### 4. Application of FCG Dynamic Control to Chiba No. 6 Blast Furnace

This study showed that FCG dynamic control has the potential to prevent segregation of the mixed layer and to achieve a uniform radial mixed coke ratio. The charging pattern with FCG dynamic control in commercial plant was examined using the mathematical burden distribution model and scale model experiment. The targets of burden distribution control with FCG dynamic control were to achieve a uniform mixed coke layer and to increase the mixed coke ratio. The calculated results of the mixed coke ratio and \( Lo/(Lo+Lc) \) distribution with FCG dynamic control are shown in Figs. 16 and 17 in comparison with the current pattern (conventional). Here, the \( Lo/(Lo+Lc) \) distribution means the real \( Lo/(Lo+Lc) \) distribution considering the mixed coke in the ore layer. \( Lo \) and \( Lc \) are the thicknesses of the ore layer and coke, respectively. FCG dynamic control enables improvement of radial coke mixing based on the concept of uniform \( Lo/(Lo+Lc) \) distribution. A scale model experiment was performed to confirm the effects of the new charging pattern with FCG dynamic control. Figure 18 shows the result of cross-sectional observation after charging. At the periphery, the small coke in the O2 batch was uniformly mixed in both cases. The experimental results confirmed that the amount of segregated coke at the center is reduced by using FCG dynamic control. Image analysis was performed by the above-mentioned method to quantify the actual coke mixed ratio. Figure 19 shows the image analysis result of actual mixed coke ratio in comparison with the base and the case with FCG dynamic control.
ratio was improved 10.3% in the case with FCG dynamic control than the base condition. 

Figure 20 shows the relationship between mixed coke ratio and relative pressure drop at cohesive zone, which is calculated the gas resistance of cohesive layer and that of coke layer using Sugiyama’s formula and Ergun’s formula respectively with the experiment result of the under-load-reduction test system.16) The result of image analysis in Fig. 19, actual coke mixed ratio was improved 12.4 kg/t in the case of Chiba No. 6 blast furnace which is conducted 120 kg/t coke mixed ratio operation, then gas permeability at cohesive zone is estimated to be improved about 13.6%.

The effect of FCG dynamic control on improvement of the mixed coke ratio was confirmed in the case of the commercial plant, and FCG dynamic control was systematically applied to Chiba No. 6 blast furnace beginning in June 2007. Figure 21 shows the FCG dynamic control pattern at commercial plant. The coke discharging speed was gradually increased with the starting of simultaneous discharging while the ore discharging speed was kept constant.

Table 2 shows a comparison of the operational data for conventional charging (period A) and with FCG dynamic control charging (period B). These are the average data of daily data during 1 month. After application of this technique, improving of both gas utilization ratio and gas permeability were observed, in spite of burden properties were almost kept constant during both periods. Concerning tapping data, hot metal temperature increase about 10 K, Si and S content in hot metal were almost kept constant.

Figure 22 shows gas utilization efficiency distribution obtained by the shaft gas sampler before and after FCG dynamic control application. The gas utilization efficiency...
increases at the middle part in radial direction (r/R=0.2–0.5) by FCG dynamic control. Figure 23 shows the relationship between Coke ratio and permeability index before and after FCG dynamic control application. The permeability index generally increases as coke ratio decreases, lower permeability index was kept after FCG dynamic control application. Figure 24 shows the pressure drop distribution obtained by shaft pressure gauge before and after FCG dynamic control application. The pressure drop in the part of shaft lower (differential the value of B3 and S3) was decrease 32.3 kPa to 27.5 kPa (decrease 14.7%) after FCG dynamic control application. This effect of decreasing pressure drop was almost corresponding to the estimated value in Fig. 20. The improvement of mixed coke yield was supposed to be contributed to these effects.

Improvement of gas permeability resulted in a decrease in the coke ratio at a constant RAR. The average data from June to July 2007, compared with the base condition, are gas utilization efficiency: +0.2% and coke ratio: −4.2 kg/t (RAR 488 kg/t). Chiba No. 6 blast furnace has remained in stable operation with high productivity and low RAR.

5. Conclusions

A controlling method of the radial mixed coke ratio distribution under high coke mixed charging, which is called FCG (Flow Control Gate) dynamic control method, was studied with the aim of stable operation with high productivity and low RAR at Chiba No. 6 blast furnace. For this purpose, scale model experiments and mathematical burden distribution model calculations were performed. The effects of FCG dynamic control on the mixed coke ratio distribution were examined and applied to Chiba No. 6 blast furnace. Since June 2007, high productivity operation with low RAR has been conducted at Chiba No. 6 blast furnace. The following results were obtained.

1. In the case of coke and ore simultaneous charging with reverse tilting, FCG (Flow Control Gate) dynamic control with a gradual increase in the coke discharging rate or gradual decrease in the ore discharging rate, or combination of them improved the uniformity of the mixed coke ratio distribution.

2. The yield of mixed coke in the ore layer increased by 8–10%, and the standard deviation of radial coke mixed ratio was improved by FCG dynamic control.

3. By FCG dynamic control, actual coke mixed ratio was supposed to increase 12.4 kg/t in the case of Chiba No. 6 blast furnace, which is conducted 120 kg/t coke mixed ratio operation, and the gas permeability at cohesive zone is estimated to be improved about 13.6%. This estimated value was almost corresponding to the value of commercial plant (14.7%).

4. After application of FCG dynamic control to Chiba No. 6 blast furnace in June 2007, improvements of gas utilization efficiency: +0.2%, gas permeability at cohesive zone (the part of lower shaft) : −14.7% and coke ratio: −4.2 kg/t (with constant RAR) were confirmed.

REFERENCES