Development of New Charging Technique for Mixing Coke in Ore Layer at Blast Furnace with Center Feed Type Bell-less Top

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Improved permeability and increased gas utilization have been desired in order to achieve low coke rate operation of blast furnaces. Coke mixed charging in the ore layer is one of the effective measures for realizing these improvements. A new charging technique for mixing small coke in the ore layer at a blast furnace with a center feed type bell-less top was developed and investigated in an experiment with a 1/18.8 scale model of an actual blast furnace at JFE Steel. By the new charging technique that small coke was charged in the determined port of the upper bunker before ore was charged in the upper bunker, the discharge pattern of the mixed small coke discharged from the bell-less top was improved, and the radial distribution of the mixed small coke ratio at the furnace top after the mixed materials were charged in the blast furnace was also improved. The new charging technique was applied to an actual blast furnace at JFE Steel, and improvement of gas permeability and a decrease in the coke rate were confirmed.

KEY WORDS: blast furnace; coke mixed charging; burden distribution; small coke, mixed coke ratio; permeability; bell-less top.

1. Introduction

Reduction of CO₂ emission from the steel industry has become an important issue in recent years. In the steel works, the ironmaking process accounts for 70% of total energy consumption.1) Therefore, research on low reducing agent rate and low coke rate operation of the blast furnace has been carried out with the aim of reducing energy consumption in the ironmaking process. Improvement of reducibility and permeability is important for achieving these operational conditions, and one measure for realizing this is coke mixed charging in the ore layer.2–10) Small coke in which the particle diameter is near to sinter particle diameter has mainly been used for this type of charging. In recent years, the mixed coke rate has been increasing gradually,7,8) and lump coke has also been used as the mixed coke in the ore layer together with small coke.11–13) Low coke rate operation was achieved by massive mixing of coke in the ore layer.

In mixing coke in the ore layer at the blast furnace, a measure in which the ore and coke were discharged from the ore bin at stockhouse was applied,2,4,14,15) but differences in the diameter and density of the ore and coke caused segregation during transport from the stockhouse to the top bunker.16–19) When the ore and coke separated after charging of these materials in the furnace top, the effect of this technique in improving reducibility and permeability decreased. Thus, to prevent segregation during transport, mixing of the ore and coke near the point of discharge in the furnace top is necessary. At a blast furnace with a bell-less top of the 3 parallel bunker type, coke and ore mixed charging was carried out by simultaneous discharge of the ore and coke using 2 top bunkers.20) Coke and ore mixed charging was also investigated at a blast furnace with a center feed type bell-less top. Kadowaki et al.20) investigated the discharge behavior of the mixed coke from the center feed type bell-less top and the mixed coke ratio distribution in the center feed type bell-less top by a scale model experiment. Their investigation showed that the fluctuation of the mixed coke ratio discharged from the bell-less top is high because of segregation of the mixed coke in the top bunker. However, measures to improve the discharge pattern so as to secure low fluctuation were not investigated. The author et al.14) showed that the mixed coke ratio in the initial stage of discharge from the top bunker could be controlled by changing the discharge pattern of the mixed coke from the ore bin at the stockhouse. However, the mixed coke ratio in the middle and final stages of discharge from the top bunker could not be controlled by this method. At the blast furnace with the center feed type bell-less top, the method of simultaneous discharge of ore and coke by using 2 top bunkers to prevent coke segregation could not be applied because only one line is used.
for transport from the stockhouse to the furnace. Thus, to improve the discharge pattern of the mixed coke from the top bunker by controlling the mixed coke ratio in the later stage of discharge at the blast furnace with the center feed type bell-less top, it was necessary to apply a new charging method in which the ore and coke are mixed during discharge from the top bunker, like the simultaneous discharge method which prevents coke segregation in the top bunker, and not the conventional method in which the coke and ore are mixed at the stockhouse.

In this study, a scale model experiment was carried out to develop a new charging technique for controlling the discharge pattern of the mixed coke from the top bunker at the blast furnace with the center feed type bell-less top. Next, the effect of the charging method on the mixed coke ratio distribution of the materials charged in the furnace top was investigated by a scale model experiment. Finally, an operating test in which the new charging method was applied was carried out at JFE Steel’s East Japan Works (Keihin District) No. 2 blast furnace.

2. Experimental Procedure

Figure 1 shows the concept of the new charging method. In the conventional charging method in which small coke and ore were mixed before the materials were charged in the top bunker, the mixed small coke segregated in the top bunker, and the mixed coke ratio in the final stage of discharge from the top bunker decreased. Therefore, a new charging method in which the small coke was charged in the top bunker before the ore was charged in the top bunker was investigated by a scale model experiment.

Figure 2 shows a schematic illustration of the experimental apparatus. The experimental apparatus is a 1/18.8 scale model of JFE Steel’s Keihin No. 2 blast furnace, which has a bell-less type charging system with a center feed type bell-less top. The length of the chute is 266 mm and the radius of the throat is 585 mm. The scale model consists of an ore bin, a coke bin, a surge hopper, belt conveyers, a bell-less top and a model furnace to simulate the charging system of the actual blast furnace. In this experiment, the Froude number, which is the ratio of inertia to gravity, was matched with that of the actual blast furnace, and the charging rate and rotation speed (39.0 rpm) were decided based on the actual charging conditions. The furnace body has 12 holes in the lower part for air blowing during charging, and an electric feeder was set under furnace body to simulate burden descent. Air is blown into the lower shaft to simulate the inclination of the burden surface while the materials are being charged.

Sinter and coke used at the actual blast furnace were crushed and used as the charged materials in this experiment. The particle size distributions of the coke, small coke and sinter were decided on the basis of the particle size distributions of the coke, small coke and sinter used at the actual blast furnace. Figure 3 shows the particle size distributions of the coke, small coke and sinter used in this experiment. The materials were charged by the same charging method as that at Keihin No. 2 blast furnace, that is, one coke batch (C) and two ore batches (O1, O2) per charge. The small coke was mixed into both ore batches (O1, O2) on the belt conveyer. In this experiment, the discharge of small coke and ore were started simultaneously, and the discharge of small coke was finished when one-fourth of the ore weight was discharged. The charging weight and charging time of each batch are shown in Table 1. The coke rate was 380 kg/t.
The method of charging the small coke in the upper bunker, the number of small coke ports charged in the upper bunker and the discharge time lag of the small coke from the upper bunker to the lower bunker were investigated for the development of the new charging method. The experimental conditions are shown in Table 2. When small coke was charged in one port in the upper bunker, the upper rotating chute in the upper bunker was stopped, and the small coke was charged in the port. Thereafter, the ore was charged in all the ports. The discharge time of the materials from the upper bunker to the lower bunker was about 3 seconds.

The change in the mixed coke ratio of the materials discharged from the lower bunker was measured. Figure 4 shows a schematic illustration of the experimental apparatus for collecting the mixed materials discharged from the bell-less top. A series of boxes, a belt conveyer and a roller conveyer were set under the lower bunker. The mixed materials discharged from the lower bunker were collected in the series of boxes moving on the belt conveyer, and the collected mixed materials were separated by the gravity separation method. The condition of the charging materials in this experiment was O1.

To investigate the effect of the stacking condition of the small coke in the lower bunker on the discharge behavior of the small coke from the lower bunker, an experiment was carried out in order to observe the stacking condition of the small coke in the lower bunker. The acrylic rectangular model shown in Fig. 5 was used, and the diagonal ports were located on the observation side. The weight of the charging materials in this model is one tenth of the weight shown in Table 1 because the inner volume of the rectangular model is about one-tenth that of the top bunker of the scale model shown in Fig. 4. The condition of the charging materials in this experiment was O1. In this experiment, colored sand (white) with the bulk density of 540 kg/m³, which is near the bulk density of coke (560 kg/m³), was used as the small coke in order to distinguish the coke mixed in the ore. The particle size distributions of the colored sand were adjusted to be the same as the particle size distributions of the small coke shown in Fig. 3.

Table 1. Charging conditions.

<table>
<thead>
<tr>
<th></th>
<th>Experiment</th>
<th>Actual BF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Charging weight (kg)</td>
<td>Charging time (s)</td>
</tr>
<tr>
<td>Coke</td>
<td>4.42</td>
<td>43.1</td>
</tr>
<tr>
<td>Ore1 + Small coke1</td>
<td>14.72 + 0.49</td>
<td>21.5</td>
</tr>
<tr>
<td>Ore2 + Small coke2</td>
<td>9.02 + 0.40</td>
<td>13.8</td>
</tr>
</tbody>
</table>

Table 2. Experimental conditions.

<table>
<thead>
<tr>
<th></th>
<th>Charging method of small coke into upper bunker</th>
<th>Number of small coke ports (−)</th>
<th>Discharge time lag of small coke (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>mixing with ore before charge into upper bunker</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Case1</td>
<td>charging separately before charge of ore</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Case2</td>
<td>charging separately before charge of ore</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Case3</td>
<td>charging separately before charge of ore</td>
<td>1</td>
<td>0.3</td>
</tr>
<tr>
<td>Case4</td>
<td>charging separately before charge of ore</td>
<td>1</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Fig. 4. Schematic illustration of experimental apparatus for collecting mixed materials discharged from bell-less top.

Fig. 5. Schematic illustration of rectangular model.
furnace top. A low viscosity liquid resin was poured from the surface of the burden, and a sample was cut off after the resin had solidified in order to observe the cross section of the burden. Image analysis\(^{12}\) was performed to quantify the mixed coke ratio distribution in the ore layer containing mixed coke, and the mixed coke yield in the ore layer was quantified. First, the sample was divided into a mesh with the radius of 20 and height of 10. The ore layer in the mesh was the analysis area. Next, the area ratios of the coke and ore in each mesh were calculated by using binary data based on the difference of brightness of the coke and ore. The area ratios were integrated in the circumferential direction at each radial position for conversion to the volumes of the coke and ore. Finally, the weights of the coke and ore were calculated by each volume and density. In this analysis, the outermost area of the analysis area (central area, peripheral area, surface of ore layer and between coke layer and ore layer) was excluded from the analysis as not mixed coke. The mixed coke yield in the ore layer was defined as the ratio of the mixed coke weight obtained by the analysis to the charged weight of the mixed coke. In the observation of the cross section, the colored sand (white) applied to the rectangular model experiment was used as the small coke in order to distinguish the coke mixed in the ore.

3. Experimental Results and Discussion

3.1. Effect of Small Coke Charging Method on Discharge Behavior of Small Coke from Top Bunker

Figure 6 shows the effect of the method of charging the small coke into the upper bunker on the discharged weight ratio of the mixed coke ratio discharged from the top bunker. The mixed coke ratio is the ratio of the coke weight to the weight of the coke and ore, and the discharged weight ratio is the ratio of the integrated weight of the collected materials to the total collected weight. The mixed coke ratio discharged from the lower bunker in the final stage in Case 1 and Case 2 was higher than that in Base. Thus, the charging method in which the small coke was charged was started was effective for increasing the mixed coke ratio in the final stage of discharge.

At Keihin No. 2 blast furnace, the ore is charging by reverse tilting,\(^{25}\) which is the method of charging from the central part to the peripheral part. This means the initial materials discharged from the lower bunker are charged in the central part of the furnace top. When that the mixed coke ratio in the initial stage of discharge was high, a large amount of small coke descended to the deadman because the deadman coke was replaced by the coke charged in the central part of the furnace top.\(^{26}\) When the voidage of the deadman coke decreased as a result of mixing of small coke in the deadman, the pressure drop in the blast furnace increased\(^{27}\) and the residual amount of slag and metal in the blast furnace increased.\(^{28}\) Thus, the most suitable method of charging the small coke in the upper bunker is Case 2 because the mixed coke ratio in the final stage of discharge is high and the mixed coke ratio in the initial stage of discharge is low.

Figure 7 shows the effect of the method of charging the small coke in the lower bunker on the discharged weight ratio of the mixed coke ratio discharged from the top bunker. The mixed coke ratio discharged from the lower bunker in the initial stage in Case 3 and Case 4 was lower than that in Case 2. Thus, the charging method in which the discharge of the materials in the port where the small coke was charged was started after the discharge of the materials in the ports other than the port where the small coke was charged was started was effective for decreasing the mixed coke ratio in the initial stage of the materials discharged from the lower bunker.

When the discharge time lag of the materials discharged from the small coke port was increased, the mixed coke ratio in the initial stage of the materials discharged from the lower bunker deceased. However, the mixed coke ratio in the final stage of the materials discharged from the lower bunker also decreased. Figure 8 shows the effect of the discharge time lag of the materials from the small coke port on the standard deviation of the change in the mixed coke ratio discharged from the top bunker. In this experiment, the mixed coke ratio in the initial stage of discharge was intentionally decreased. Therefore, this mixed coke ratio was estimated by the standard deviations of the conditions except the mixed coke ratio between 0.0 and 0.1 of the discharged weight ratio, as it was thought that the effect of the mixed coke ratio in the initial stage of discharge on the standard deviation should be excluded. As a result, an optimum condition for the discharge time lag of the materials discharged from the small coke port existed. In this experi-

![Fig. 6. Change in mixed coke ratio discharged from top bunker.](image-url)

![Fig. 7. Change in mixed coke ratio discharged from top bunker.](image-url)
ment, the standard deviation of Case 3 was the smallest. Thus, the charging method of Case 3 was the most suitable method for charging the small coke.

### 3.2. Effect of Small Coke Stacking Condition on Discharge Behavior of Small Coke from Top Bunker

Regarding the materials discharged from the lower bunker, the materials stacked on the side near the flow control gate were discharged in the initial stage and the materials stacked on the far side from the flow control gate were discharged in the final stage.23,24) Therefore, it was thought that the discharge pattern of the mixed coke ratio from the lower bunker changed depending on the stacking condition of the small coke in the lower bunker.

Figure 9 shows the stacking conditions of the ore and small coke charged in the lower bunker of the rectangular model in Base, Case 2 and Case 3. In Base, the small coke segregated in the bunker because it mixed with the ore before the materials were charged in the top bunker. As a result, the mixed small coke ratio in the final stage of discharge decreased due to the small amount of small coke stacked in the peripheral part of the lower bunker discharged in the final stage.14) In Case 2, most of the small coke charged in the upper bunker initially was also charged in the lower bunker initially. As a result, the small coke was stacked at the side near the flow control gate and in the lower part of the peripheral part. In Case 3, the ore of the ports except the small coke port was charged in the lower bunker initially, and the ore was stacked at the side near the flow control gate. Thus, the small coke was not stacked at the side near the flow control gate but was stacked in the slightly upper part of the stacking area of the small coke in Case 2.

Figure 10 shows schematic illustrations of the stacked materials in the top bunker and the discharge behaviors of the materials from the lower bunker in Case 2 and Case 3. In Case 2, the mixed coke ratio discharged from the lower bunker in the final stage increased because the small coke stacked in the peripheral part was discharged in the final stage. In Case 3, the mixed coke ratio discharged from the lower bunker in the initial stage decreased because the ore stacked at the side near the flow control gate was discharged.
in the initial stage.

As a result, this new charging method (Case 3), in which the small coke charging method was changed, was a method that made it possible to control the discharge pattern of the small coke from the lower bunker by changing the stacking area of the small coke in the lower bunker widely.

3.3. Effect of Small Coke Charging Method on Mixed Coke Ratio Distribution at Furnace Top

Figure 11 shows the results of measurements of the surface profiles after charging. In Base and Case 3, the new charging method which was estimated to be the most suitable in section 3.1, the measurement results were compared. Both results showed similar surface profiles. Figure 12 shows the effect of the small coke charging method on the radial distribution of the mixed coke ratio. In Base, the mixed coke ratio at the central part was high because the mixed small coke ratio in the initial stage of discharge from the top bunker was high, as shown in Fig. 6, and the materials discharged in the initial stage were charged in the central part of the furnace top by reverse tilting. In Case 3, the mixed coke ratio at the central part was low because the mixed small coke ratio in the initial stage of discharge from the top bunker was low, as shown in Fig. 7, and the materials discharged in the initial stage were charged in the central part of the furnace top by reverse tilting. The mixed coke ratio was high at $r/R = 0.5–0.8$, which was near the top of the heap charged in the last rotation of the chute, because the mixed small coke ratio in the final stage of discharge from the top bunker was high, as shown in Fig. 7. Figure 13 shows the observed results of the cross sections after charging. Figure 14 shows the calculated result of the surface profiles of the ore layer charged by one rotation by using the burden distribution simulation model (Base). In Base, the mixed coke ratio at the upper part of ore layers O1 and O2 was low because the mixed coke ratio in the final stage of discharge from the top bunker was low. In Case

![Fig. 11. Comparison of surface profiles after charging.](image1)

![Fig. 12. Effect of small coke charging method on radial distribution of mixed coke ratio.](image2)

![Fig. 13. Comparison of cross sections after charging.](image3)

![Fig. 14. Calculation result of surface profiles of ore layer charged by one rotation.](image4)
3, the mixed coke was charged homogeneously. Thus, the new charging technique in which the small coke charging method was changed made it possible to control the radial distribution of the mixed coke ratio at the furnace top while maintaining the surface profile.

**Figure 15** shows the effect of the small coke charging method on the mixed coke yield in the ore layer. The mixed coke yield in Case 3 was 11% higher than that in Base. Improvement of permeability in the blast furnace was expected because of the decrease in pressure drop in the cohesive zone resulting from the increase in the mixed coke yield.¹²)

As a result, when using the new charging technique, in which the small coke was charged in one port of the upper bunker and the discharge of the materials in the port where the small coke was charged was started 0.3 sec after starting the discharge of the materials at the ports other than the port where the small coke was charged, the mixed coke yield in the ore layer increased and improvement of the permeability in the cohesive zone was expected.

### 4. Operational Test for Examination of Change in Small Coke Charging Method at Keihin No. 2 Blast Furnace

To estimate the effect of the new charging technique on the operation of the actual blast furnace, an operational test was carried out at Keihin No. 2 blast furnace. At Keihin No. 2 blast furnace, coke is charged in one batch (C) and ore is charged in two batches (O₁, O₂). Before the test operation, the small coke was charged by the conventional method, which corresponds to Base in the scale model experiment. The new charging technique, i.e., Case 3 in the scale model experiment, was applied during test operation. The discharge time lag in this test was decided to be 1 sec, which is the estimated value when the Froude number of the actual condition was near that of the experimental condition. The small coke charging method was changed in both ore batches, and the discharge time lag was 1 sec in both ore batches.

**Figure 16** shows the typical permeability index before and after the change in the small coke charging method. The permeability index increased due to the decrease in coke rate, generally. However, at the same coke rate, the permeability index after the change in the small coke charging method was lower than that before the change. **Figure 17** shows the distribution of the increased pressure from the top gas pressure obtained by shaft pressure gauges (S₁–S₇) before and after the change in the small coke charging method. After the change in the small coke charging method, the pressure drops in the lower shaft (S₁, S₂) decreased. It is thought that the mixed coke yield improved and the pressure drop in the cohesive zone decreased due to the change in the small coke charging method.

As a result, although further investigation may be necessary in order to determine the most suitable charging conditions, the new charging technique in which the small coke charging method was changed is an effective control measure for reducing the permeability resistance of the blast furnace by improving the mixed coke ratio at the blast furnace with the center feed type bell-less top.
5. Conclusions

A charging technique to improve permeability of blast furnace by controlling the mixed coke ratio distribution in the ore layer was investigated at a blast furnace with a center feed type bell-less top. First, a new charging technique for controlling the discharge pattern of the mixed coke discharged from the top bunker was investigated in a scale model experiment. Then, the effect of the new charging technique on the mixed coke ratio distribution in the ore layer stacked in the furnace top was investigated in a scale model experiment. Finally, the effect of the new charging technique on the operation of the actual blast furnace was investigated. The following conclusions were obtained.

(1) The charging method in which small coke was charged in one determined port of the upper bunker before ore was charged in the upper bunker prevented segregation of the small coke in the top bunker, and the mixed coke ratio of the materials in the final stage of discharge from the lower bunker increased. The charging method in which the materials of the port where the small coke was charged were discharged in the lower bunker after the discharge of the materials of ports other than the port where the small coke was charged reduced the mixed coke ratio of the materials in the initial stage of discharge from the lower bunker.

(2) The charging method in which discharge into the lower bunker of the materials in the port where the small coke was charged was started after discharge into the lower bunker of the materials in the ports other than the port where the small coke was charged improved the radial distribution of the mixed coke ratio and increased the mixed coke yield in the ore layer.

(3) An operational test of the new charging technique, in which the small coke charging method was changed, was carried out at Keihin No. 2 blast furnace. The permeability index was decreased by application of the new charging technique.

REFERENCES