Effect of Coal Size Segregation in Coal Bin on Discharging Coke Cake

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For improving the performance of discharging coke cake from oven chambers, the way to increase clearance between coke cake and oven wall near coke side was investigated. To avoid a pushing trouble is needed because this trouble, which has increased gradually with the aging of coke ovens, negatively affects the stable coke production and service life of coke ovens. One of the effective approaches to improve the discharging conditions is to maintain the sufficient clearance especially near coke side because the oven walls around there have been most damaged in aging coke ovens. Therefore enlarging the clearance near coke side was studied.

For this objective, it was focused on the way to decrease coal size and bulk density locally by controlling the coal size segregation in coal bin. Firstly, the effects of coal size and bulk density on the clearance were examined at laboratory. Then the effects of the charging conditions of coal blend on the size segregation and the clearance were investigated. As a result, the clearance increased with decreasing the coal size and bulk density. Moreover, the clearance was capable of variation by size segregation.

Based on the laboratory-scale study, a commercial plant trial was conducted. Consequently, it was clarified that the discharging behavior was improved by size segregation although the variation of the coal size was smaller than we initially envisioned.

KEY WORDS: cokemaking; pushing trouble; coke cake; clearance; size segregation; bulk density.

1. Introduction

To avoid a pushing trouble is needed because the trouble, which has increased gradually with the aging of coke ovens, negatively affects the stable coke production and service life of coke ovens. One of the effective approaches to improve the performance of discharging coke cake is to keep sufficient clearance between the coke cake and the oven wall. Effects of the operational conditions of coke ovens and the blending parameters of raw coal on the clearance have been investigated.1–9) However, it is difficult to change these conditions for controlling the clearance because both coke productivity and quality also relate to these conditions. Therefore it was considered that enlarging the clearance locally was an efficient way because the degree of the influences on both coke productivity and quality was limited compared to changing the operational conditions and blending parameters.

Meanwhile, because the degree of the wall damage is different from place to place of coke oven, there should be a bottleneck in the oven chamber. This bottleneck dominates the pushing conditions while coke cake is discharged. In laboratory-scale investigation, it is clarified that the pushing force is exponentially increased as height of the protrusion which is set on the oven wall is increased.11) In general, the wall bricks around coke side have been most damaged at old coke ovens. As a result, the clearance near coke side should have a critical effect on the pushing conditions.

For these reasons, the objective of this research is set to enlarge the clearance near coke side locally. In particular, size segregation of coal grains in coal bin was focused on as the way to set comparatively fine coal grains and to decrease the bulk density near coke side.

Figure 1 shows the conceptual diagram of this new method. As the coal charging position into coal bin is shifted toward coke side, the top of the coal pile is also shifted. The fine coal grains are piled up under the top of the pile because of the size segregation. Therefore the coal size in larry car near coke side becomes small as the coal size in coal bin near coke side becomes small. As the coal size becomes small, the bulk density of coal packed bed after charging into the oven chamber is generally decreased. Consequently, the clearance near coke side should be enlarged because it is said that the clearance is increased as the bulk density of coal blend is decreased.5, 6) In addition, coal size relates to the generation behavior of cracks or fissures in coke cake and the number of cracks or fissures which are strongly connected with the clearance.7–10)

At the beginning of this research, the effects of coal size
and bulk density on the clearance were examined at laboratory. The effects of charging conditions of coal blend on the coal size segregation, bulk density and clearance were also investigated. After that, in order to evaluate the commercial scale impact of the size segregation on pushing conditions of coke cake, a plant trial was carried out.

As the results of these studies, it was found that the clearance was enlarged with decreasing the coal size and the bulk density. Moreover, it was clarified that the discharging behavior of coke cake was improved by controlling the coal size segregation in coal bin especially for the chambers whose pushing load was constantly high.

2. Laboratory Investigation

2.1. Experiment

2.1.1. Measurement of Clearance

For quantifying the effects of coal size and bulk density of coal blend on the clearance, the carbonization tests and measurements of the clearance on the carbonized coke cake were conducted as below. The characterization data of the coal brands used in these tests and those blending ratios for making the sample coal blends are shown in Table 1. At first, the coal brands were individually crushed and sieved so that the weight ratio of the coal whose particle diameter was less than 3 mm, which was defined as the coal size index (–3 mm wt%), became 65, 75 and 85 wt%. Then those brands were mixed so that those blending ratios were set values. The bulk density levels were set to be 725, 750 and 775 kg/m³ when the samples were carbonized. Those test levels and the properties of sample coal blends were set based on the commercial conditions. The schematic illustration of the experimental apparatus used in the carbonization test is shown in Fig. 2. The samples were packed into a brick container (W190 × H120 × L114 mm) at the set bulk density. The 3 same samples were carbonized at the same time in laboratory-scale coke oven at 1050°C for 4 h 20 min. The sample coal was heated through the wall made of

![Conceptual diagram of the way to control coal size segregation in coal bin.](image1)

![Schematic illustration of experimental apparatus for measuring clearance between coke cake and wall.](image2)
hardly deformable carbon plate during carbonization. After dry quenching, the carbon plates were changed for reference plates. Then the distance between the coke cake and the wall was measured by laser displacement at 5 mm intervals at the measurement range (H95 × L100 mm) per one plane of the coke cake. If the measured distance exceeded 20 mm, the data were ignored as the outliers due to cracks or fissures of the coke cake. Each mean value of those data per one plane was calculated. Then a total value of the two mean values on heated planes per coke cake was defined as the clearance of the coke cake. In order to analyze the effect of the coal size on the cracks or fissures in the coke cake, whose set bulk density was 775 kg/m³, the X-ray CT (Shimadzu: SCT-4800TF) images of the center of the coke cake were taken so that these images were parallel to the heating direction. The X-ray tube voltage, tube current and exposed time were set to 120 kV, 200 mA and 2.8 s, respectively.

2.1.2. Evaluation of Size Segregation

For evaluating the size segregation of coal grains in coal bin at commercial plant, the laboratory-scale charging tests were carried out for the several conditions. Furthermore, the effect of the coal size after the size segregation on the bulk density and the clearance were also measured. The sample coal was taken from commercial coal blend of Kurashiki No. 3, 4 coke ovens (hereinafter referred to as a “Base sample”). The test levels of the coal moisture content, which affects the coal handling, were set to 7–12 wt% as shown in Table 2 for simulating the range of operating conditions. The moisture content of each sample was regulated so as to be the set value by blending the coal blend and deficient water within a mixer. The schematic illustration of the experimental apparatus is shown in Fig. 3. A board was set in order to simulate the slope face of the coal pile in coal bin. Based on the relationship between the moisture content of coal and the repose angle, the angle between board and ground was set to 34–40° as shown in Table 2. The sample coal was constantly fed at 125 kg/(s m) (the feeding speed per unit width of belt feeder was referred to the commercial condition) above top of the board via the belt feeder and piled up on the board. A few kilo grams of the samples for measuring the size were taken from the sampling places by an increment shovel as shown in Fig. 3. The coal taken from the same level was mixed together as a same sample. The upper half sample was named “Supposing hole A sample” because the sample was supposed to pass through the charging hole A which is nearest coke side as shown in Fig. 1. In a similar way, the lower half sample was named “Supposing hole B sample”. The coal size of each sample was measured after it was dried. Next, free-fall tests, carbonization tests and measurements of clearance were implemented under the condition that the coal moisture content was 7 wt%. The samples for free-fall tests were prepared as below. The Base sample for charging test was crushed and sieved so that the coal size became congruent with the sample coal after charging test. Then the moisture content was regulated so as to be the set value by blending coal and deficient water within a mixer. The schematic illustration of the apparatus for free-fall test is shown in Fig. 4. 38 kg of the samples

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Moisture content (wt%)</th>
<th>Repose angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7</td>
<td>34.0</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>37.5</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>40.0</td>
</tr>
<tr>
<td>4</td>
<td>12</td>
<td>40.0</td>
</tr>
</tbody>
</table>

Table 2. The levels of the laboratory-scale charging test.

Fig. 4. Schematic illustration of experimental apparatus for free-fall test.

Fig. 3. Schematic illustration of experimental apparatus for charging test.
were fallen freely from 3.0 m above into a box. The gap between hopper and ground was set in accordance with the half of height between the charging hole and the bottom of commercial chamber for evaluating the mean value of the bulk density of the coal packed bed within the chamber. The bulk density of each sample was calculated by using the measurement of samples’ weight within the box. Then the samples after charging tests were divided so as to be about 6 kg as the samples for carbonization tests. The moisture content of the samples was regulated so as to be 7 wt% by using a mixer. The samples were carbonized at the bulk density based on the free-fall tests and the clearance was measured according to the aforementioned way.

2.2. Results and Discussions

2.2.1. Relationship between Coal Size, Bulk Density and Clearance

Figure 5 shows the relationship between the coal size, bulk density and clearance. The clearance was enlarged as the bulk density was decreased. In addition, the clearance became bigger as the coal size was decreased. Therefore, the clearance can be controlled by changing the coal size or/and bulk density. Figure 6 shows the X-ray CT images of the coke cake after measuring the clearance. When the coal size became bigger, the amount of cracks and fissures was increased. It was observed that the cracks or fissures generated around comparatively large coal grains (those size exhibit around a few mm or more) whose shapes were clear because of their lack of caking properties. This result is consistent with the previous report about the relationship between inert size and crack generation.\(^\text{12}\) In addition, the increase of cracks or fissures contributes the decrease of the clearance.\(^\text{8,10}\) Thus it is suggested that the phenomenon is the one of the reasons the coal size affects the clearance.

2.2.2. Effect of Charging Conditions on Size Segregation and Clearance

The size segregation was evaluated by the coefficient of segregation as below;\(^\text{13}\)

\[
C_s = \frac{P_{\text{A}} - P_{\text{B}}}{P_{\text{A}} + P_{\text{B}}}
\]

where \(C_s\) is the coefficient of segregation, \(P_{\text{A}}\) and \(P_{\text{B}}\) are the weight percentages of the coal with a grain diameter of more than 3 mm in case of Supposing hole A, B samples respectively.

The relationship between the moisture content and \(C_s\) is shown in Fig. 7. \(C_s\) represents the maximum value when the moisture content is around 10 wt%. It is considered that this result is caused by two different phenomena. One of them is the change of the repose angle. As moisture content becomes high, the repose angle increases. Then large grains roll downhill more easily. Another is change of the grain fluidity. In general, grain fluidity decreases with increasing the moisture content because of their cross-linkage force.\(^\text{14}\) So it is difficult for the coal grains to roll downhill individually. Thus it is suggested \(C_s\) represented the maximum.

Figure 8 shows the measured coal size, bulk density and
clearance when the moisture content of sample was 7 wt%. In addition, the results of the samples which were taken from the sampling place 1 and 6 (refer to Fig. 3) were also shown in the same figure. $C_S$ of this test sample indicated 0.12 as shown in Fig. 7. As the coal size became small, the bulk density was decreased and the clearance was enlarged. Moreover, the clearance of Supposing hole A sample was enlarged 0.3 mm than Base one. As a result, it was clarified that the clearance can be controlled by the size segregation of the coal grains.

3. Plant Trial

3.1. Experiment

For evaluating the commercial-scale impact of controlling the size segregation in coal bin on the discharging coke cake, a plant trial was carried out for 24 days. Kurashiki No.1 coke oven was picked out as the trial plant. Basic data about that coke oven and the operational conditions at the time are shown in Table 3. The schematic view of the experimental system is shown in Fig. 9. The coke oven had 2 coal bins. In addition, the larry cars were able to receive the coal blend from both coal bins. A charging chute was set in the one coal bin in order to control the size segregation by shifting the charging position of the coal blend toward coke side as Fig. 1. If the larry cars received the coal blend from the coal bin which include the chute, the coal near coke side in the larry car was expected to be comparatively small. Thus the difference between the case of using the coal bin which has the charging chute (hereinafter referred to as a “Developed method”) and the case of using the normal coal bin (hereinafter referred to as a “Conventional method”) was evaluated. From 7:00 a.m. to 5:00 p.m. per day of trial period, the developed method was applied. In contrast, the conventional method was employed during the rest of the time. The samples were taken from each hopper of the larry cars for measuring coal size. Moreover the maximum power current of pusher, which had a close relationship to the pushing load and the degree of discharging coke cake, was measured with each pushing cycle from 20 days before the start of the trial through 16 days after the end of the trial. The operational conditions in Table 3 were kept constant during trial period because those factors strongly relate to the pushing conditions. The moisture content was kept approximately 9.2 wt% which was included the range that the coal grains should be well segregated according to Fig. 7.

3.2. Results and Discussions

3.2.1. Effect of the Developed Method on Size Segregation

The size data of hole A and B samples between conventional and developed methods are shown in Fig. 10 ($C_S = (P_{\text{Hole B}} - P_{\text{Hole A}})/(P_{\text{Hole B}} + P_{\text{Hole A}})$, where $P_{\text{Hole A}}, P_{\text{Hole B}}$ are

![Fig. 8. Effect of size segregation on coal size, bulk density and clearance.](image)

![Fig. 9. Schematic view of experimental system of plant trial.](image)

<table>
<thead>
<tr>
<th>Specification of coke oven</th>
<th>Type</th>
<th>Carl Still</th>
</tr>
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<tbody>
<tr>
<td>Age (year)</td>
<td>42</td>
<td></td>
</tr>
<tr>
<td>Total of chambers (-)</td>
<td>78</td>
<td></td>
</tr>
<tr>
<td>Dimension (m)</td>
<td>$W0.44 \times H6.71 \times L14.8$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Operational conditions</th>
<th>VM (wt% d.b.)</th>
<th>Moisture content (wt%)</th>
<th>Coal size (~3 mm wt%)</th>
<th>Flue temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>28.2</td>
<td>9.2</td>
<td>75</td>
<td>1155</td>
</tr>
</tbody>
</table>
the weight percentages of the coal samples taken from hole A, B with a grain diameter of more than 3 mm respectively). In case of the conventional method, the coal size of charging hole A sample was comparatively large because that sample mainly contained the coal which existed at skirt of the coal pile in coal bin. After applied the developed method, the coal size of charging hole A sample became smaller. Therefore it is implied that the developed method increase the clearance near coke side. However the impact of the size segregation at commercial plant was smaller than the one at laboratory. The reason is considered that the amount of coal which rolled downhill to hole B is limited because the coal segregates in a radial fashion from the top of pile at commercial plant.

3.2.2. Improvement Impact of the Developed Method

As an example, the profiles of the power current of pusher are shown in Fig. 11. The maximum value of the power current was collected except notched noise. That value indicates the index of pushing load.

The distribution histograms of the maximum power current of pusher are shown in Fig. 12. In this analysis, if the gross coking time (GCT) was under 20 hours or over 30 hours, the data at that time were ignored as outliers. The reason was those cases were extraordinary operations such as deviating from a schedule. In case of the developed method, the ratio over 175A decreased. In addition, the mean of all data decreased from 185 to 177A by applied the developed method. As a result, it was found that the developed method improved the discharging behavior through the decrease of the coal size near coke side. It is considered that enlarging some degree of the clearance near coke side positively affects the discharging behavior, although the variation of the coal size at plant was smaller than the one at laboratory. It is considered that one of the additional reasons of the improvement is the internal gas pressure of coal blend. The internal gas pressure is decreased with decreasing the coal size. Moreover the developed method probably increases the temperature at the center of the chamber near coke side because the bulk density is decreased and the thermal diffusivity is enlarged. It is reported that the pushing load is increased as the temperature at the center of the chamber is decreased. Therefore it is inferred that those phenomena also affect the discharging behavior.

As a second analysis, the statistical evaluation was carried out in order to more clarify the impact of the developed method. Two-sample t-test between the maximum power current of pusher applied the conventional method and that applied the developed method was conducted for each coke chamber. The two-sided 90% confidence interval was used in this test. And it was assumed that each dispersion was different. The results are shown in Fig. 13. As applied the developed method, about 39% of the chambers obtained significantly positive effects for pushing load. However, only 5% of the chambers obtained significantly some negative effects. The reason of the negative effects was thought that their bottleneck were not near coke side but under the charging hole B. In addition, the improving impact tended to be obviously higher with respect to the chambers whose pushing load was constantly high. The comparison of the impact of developed method on the maximum power current of pusher between in case of the chambers whose pushing load was constantly high and low was shown in Fig. 14. The chambers whose pushing load was constantly high were selected in the top quarter of all chambers with applied the conventional method during the trial period. On the other hand, the chambers whose pushing load was constantly low were selected in the bottom quarter. In case of the chambers whose pushing load were constantly high, the maximum...
power current of pusher became 7% small by the developed method. In contrast, the value of the chambers whose pushing load was constantly low decreased only 2%. Thus the developed method was more effective for the chambers whose pushing load was constantly high.

4. Conclusions

(1) Clearance between coke cake and oven wall became larger as the bulk density and the coal size of coal blend before carbonized were decreased.

(2) Degree of size segregation ($C_S$) was affected by the moisture content of coal. $C_S$ indicated the maximum when the moisture content was around 10 wt%.

(3) As the results of the plant trial, it was clarified that the pushing conditions were improved by controlling the size segregation in coal bin although the variation of the coal size was smaller than the one at laboratory. In particular, the developed method was more effective for the chambers whose pushing load was constantly high.

REFERENCES