Simultaneously Overdeveloped Central and Peripheral Gas Flows of a Blast Furnace

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(Received on March 20, 2015; accepted on June 16, 2015)

The gas flow distribution in the radial direction of the blast furnace is of vital importance for its stable and economical operation.

In this study, an experimental apparatus, simulating bell-less top charging, was built on a 1/15 scale of 5 800 m³ blast furnace in Shasteel. Experimental results shows that the charging mode designed for the simultaneously overdeveloped central and peripheral gas flow leads to a thin coke slit in the intermediate part and a large center coke column in the model furnace. The intermediate coke slit is more thinner under higher U/Umf, larger O/C and deeper stock line with the existence of coke collapse; and in the radial direction, the largest fluctuation of gas velocity exists at the center-adjacent point, the interface of center coke column and ore layer, where the small particle size coke gets fluidized, which coincides with the analysis of above-burden temperature fluctuation and observation from top camera during blast furnace operation.

In combination with the actual online operation data, it is further revealed that the burden layer with locally-narrowed coke slit at the cohesive zone hinders the smooth gas flowing, resulting in a big fluctuation of gas flow at the bosh part and an unsmooth burden descending.

Optimization of charging pattern was done in the cold model and applied to the 5 800 m³ blast furnace. As a conclusion, optimization of coke charging mode to increase the intermediate thin part of coke layer is the most effective way to pursue the stable operation with high productivity.

KEY WORDS: coke collapse; center coke column; coke slit; intermediate part; fluctuation; gas flow; unsmooth burden descending.

1. Introduction

It is well known from the BF dissection results that the inverted-V shape cohesive zone is good for the economical and stable operation of a blast furnace, which requires high gas temperature in the center part and also high enough gas temperature at the peripheral part to resolve the cohesive zone root.2) From the radial gas temperature distribution patterns of above-burden probe in the blast furnace throat parts both in the low fuel operation cases of Chiba No. 6 BF with an annual average fuel ratio of 436.1 kg/t-HM,3) Fukuyama No. 3 BF with a monthly average fuel ratio of 428.2 kg/t-HM4) and Kimitsu No. 3 BF reaching a fuel ratio of 431 kg/t-HM5) and in the high productivity case of Keihin No. 2 BF up to 2.69 t/m³ in productivity,6) it is shown that the center gas flow is fairly high and the gas temperature in the peripheral part is comparatively higher than the intermediate part. To secure a strong center gas flow, the center coke charging technology has been widely applied to decrease the total blast furnace pressure drop and maintain a good liquid permeability of deadman.7–9) On the other hand, when the raw material quality deteriorates, it is necessary to keep a stronger peripheral gas flow.10) In addition to the aforementioned advantages of keeping strong center and peripheral gas flows, in Shasteel, the hot metal demand is the first priority but the raw material quality is unstable; as a consequence, the operational philosophy of “two gas flows”, strong center gas flow and peripheral gas flow, is highly pursued, i.e. using a bell-less rotating distributor to charge a large amount of coke to the center part of blast furnace to keep strong center gas flow, and charging rich coke and few ore at the wall side to keep strong peripheral gas flow. However, as pointed out by Sawada et al. in a US. patent, too strong center gas flow together with the peripheral flow is not appropriate for blast furnace operation11) and Wang et al. also found in the actual operation that, simultaneously-overdeveloped center and peripheral gas flow is no good for the blast furnace performance.12) However, up to now, there is no investigation on this phenomenon. So it is essential to construct a physical model to investigate how the burden profile behaves inside the blast furnace, how it affects the gas flow and burden descent and how it can be optimized quantitatively.

Over the past decades, a few cold charging models have been built to simulate the burden profile and the gas flow distribution, achieving many valuable findings. NISHIO et al. built a 1/10 scale 36° segment model of Fukuyama No. 5 BF and found that coke collapse during ore charging was considerable with the increase of gas flow; coke pillar was formed during ore charging due to low permeability of ore;
gas flow concentrated at the center and fluidized the coke there, blocking ore motion towards the center of blast furnace.\(^{(13)}\) JIMENEZ et al. built a 1/10 half-section model, for which Froude number was kept equal for both the model and the actual blast furnace for blast injection; it was found that small-size coke particles got fluidized and there was a narrow coke window formed in the center of the model.\(^{(14)}\) Narita et al. set up a 1/20 180° segment model of Kakogawa No. 1 BF and found that when ore is charged, gas concentrated in the central region and the coke layer expanded upward in the region where the gas velocity exceeded the minimum fluidization velocity of the coke particles, and some coke lumps in the expanded layer were pushed into the central part by the flow of charged ore.\(^{(15)}\) Narita et al. also built a full-size model and found that ore/coke was reduced at the central part with a high gas flow velocity.\(^{(16)}\) Okuno et al. set up a 1/3 model of Muroran No. 1 BF and studied the coke collapse phenomenon in detail by using a profile meter and revealed that the magnitude of coke layer collapse was mainly dominated by the charging mode rather than the burden descending velocity and gas flow.\(^{(17)}\)

In this study, a cold charging model on a 1/15 scale of 5 800 m³ blast furnace in Shasteel was built based on the similarities of the particle size distribution, the same burden falling trajectory in the open air and the same gas-packed bed interaction between the actual blast furnace and the cold model, to simulate the burden layer distribution and the gas flow distribution in the radial direction of the blast furnace. By making use of the experimental apparatus, a couple of experiments were carried out to study the effects of blast volume, the amount of center coke charging, the overall O/C, the stock line on the radial burden layer and the gas flow distribution, etc. As pointed by Okuno et al.,\(^{(17)}\) the coke was pushed into the center part of the blast furnace during ore charging due to its large kinetic energy. The actual coke thickness after ore dump was measured by an electrode-type layer thickness meter, the same one with that used by Okuno et al.\(^{(17)}\) The analysis was also carried out on the chronological change of the average coke and ore particle size during discharging from the top bunker, as well as the average coke particle size distribution in the radial direction of the model furnace. To investigate how the burden profile forms, the radial distribution of burden profile and gas flow rate after materials at each tilting angle were dumped to the throat part of the model furnace was also measured and the gas fluctuation at each radial point was analyzed. Optimization of the burden layer distribution was conducted in the cold model by adjusting coke and ore charging modes, which has been applied to the actual operation of 5 800 m³ blast furnace. In addition to the experimental study, the online operational data, especially the mechanical sounding data, the above-burden temperature and stave temperature were analyzed to reveal the internal state of the operating blast furnace.

### 2. Experiment

#### 2.1. Experimental Apparatus and Materials

A 1/15 scale and 180° segment model of Shasteel 5 800 m³ BF is shown in Fig. 1. Coke and ore batches are sequentially charged to the model furnace by an automatically-controlled rotating distributor (5), of which the rotating speed and the tilting speed are 186°/s and 15°/s respectively; at the same time, the compressed air is blown through 20 tuyeres (8) uniformly placed at the bottom of the half-cut experimental furnace. During the experiment, the stock line is controlled by an electric discharger (10) placed at the bottom of the cold model. Properties of materials used in the experiment are listed in Tables 1 and 2.

#### 2.2. Similarity Condition

Even though the dimension of the actual blast furnace is 1/15 downsized to a cold model, the difference exists in the mechanical dynamic behaviors of solid and gas flow between the actual blast furnace and the model furnace. Appropriate parameters such as particle size distribution, chute rotating speed and top gas velocity for the cold charging model are determined from fundamental equations listed in Table 3. In Eq. (1), \(d_p\) is the particle size, \(x = \ln(d_p)\), \(\sigma = \ln(D_{50})\), \(\mu = \ln(D_{90})\), D50 the particle size for 50% in weight, D15.9 the Particle size accounting 15.9% in weight. In Eq. (2), \(S\) is the scale factor of the cold charging model, 1/15. In Eq. (3), \(U_{air}\) and \(U_{ore}\) are the minimum fluidization velocity of particle for actual blast furnace and cold model respectively.

To keep the smooth flowing of coke and ore particles from the top bunker to the bottom outlet of the experimental furnace, a couple of pre-tests have been done to determine the downsize ratio of average particle size of coke and ore for the experiments, 1/12 for coke and 1/9 for ore. Lognormal distribution equation\(^{(30)}\) in Table 3 is applied to determine the weight ratio of each size class for coke and ore used for cold model, \(R(d_p)\), keeping the particle size

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**Table 1.** Properties of coke for cold model.

<table>
<thead>
<tr>
<th>Size (mm)</th>
<th>1–2</th>
<th>2–3.5</th>
<th>3.5–5.5</th>
<th>5.5–8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apparent density (kg/m³)</td>
<td>668</td>
<td>572</td>
<td>544</td>
<td>544</td>
</tr>
<tr>
<td>Repose angle (°)</td>
<td>39.0</td>
<td>37.8</td>
<td>38.5</td>
<td>40.5</td>
</tr>
</tbody>
</table>

**Table 2.** Properties of ore for cold model.

<table>
<thead>
<tr>
<th>Size (mm)</th>
<th>0.5–1.0</th>
<th>1.0–2.0</th>
<th>2.0–3.5</th>
<th>3.5–5.5</th>
<th>5.5–8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apparent density (kg/m³)</td>
<td>2.305</td>
<td>2.134</td>
<td>2.085</td>
<td>2.166</td>
<td>2.037</td>
</tr>
<tr>
<td>Repose angle (°)</td>
<td>37.5</td>
<td>37.4</td>
<td>38.4</td>
<td>41.2</td>
<td>39.7</td>
</tr>
</tbody>
</table>

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**Fig. 1.** Experimental apparatus of the 1/15 cold charging model.
distribution between the actual furnace and the cold model the same as shown in Fig. 2.

The chute rotating speed $\omega$ is determined according to the Eq. (2) in Table 3 to keep the burden falling trajectories in the open air of both the actual blast furnace and cold charging model the same, aiming to form the same burden profiles inside. For both the actual blast furnace and cold charging model, mechanical equations of the motion of a single particle on the rotating chute and in the open air are simplified as Eqs. (4) and (5) respectively:

$$V_L = \sqrt{\omega^2 \sin \theta (\sin \theta - \mu \cos \theta) L^2 + 2g(\cos \theta - \mu \sin \theta)L + V_0^2}$$

$$Y = X \cdot \cot \theta + \frac{1}{2} s \left( V_L \right)^2 \sin^2 \theta$$

Where, $V_L$: Particle velocity at the tip end of the rotating chute, $V_0$: particle velocity when it gets to upper surface of rotating chute, $\theta$: chute tilting angle, $X$: distance of particle moving in horizontal direction, $Y$: distance of particle moving in vertical direction, $L$: length of rotating chute, $\omega$: angular velocity of rotating chute. The above-listed symbols stand for the parameters of actual blast furnace, while the aforementioned symbols with a star at the top right corner stand for the parameters of the cold model. Integrate the Eqs. (4) and (5) for both actual blast furnace and cold charging model, yielding Eq. (6).

$$\sin \theta (\sin \theta - \mu \cos \theta)L^2 (\omega L - (V_0^*)^2 L) + V_0^2 L - (V_0^*)^2 L = 0$$

As a mathematical solution, both the first term and the second term in the left hand side of Eq. (6) should be 0, that is to say, the chute rotating speed $\omega = \omega_S$ and $V_0 = V_0_S$ ($S = 1/15$).

The burden flow in the open air of the cold model was measured at different tilting angles, 48.1°, 40.1°, 30.1° and 20.1° by a video camera with a capture capability of 30 frames per second which was installed 1 m away from the furnace body, pointing at the vertical section of the model as shown in Fig. 3. Rotating chute movement and the falling streams during the material charging were recorded and analyzed on the computer. When the rotating chute points at the vertical section of the model, the center positions of outer and inner boundaries of coke and ore streams are marked in white dots as falling trajectories. Besides, the burden falling trajectories of coke and ore during the material filling for blow-in of 5 800 m³ blast furnace were measured by a crossed laser beam method. As shown in Fig. 4, two laser emitters were installed at the east side and west side of the furnace top, generating laser beams from each side, intersecting to form a laser net across the center plane of the furnace. As a coke or ore stream moves across the net, the particle size distributions of coke and ore for model and actual blast furnace.

![Fig. 2. Particle size distributions of coke and ore for model and actual blast furnace.](image)

Table 3. Similarity of parameters between actual blast furnace and cold model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Actual blast furnace</th>
<th>Cold model</th>
<th>Similarity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle size distribution</td>
<td>$R_{dp}$</td>
<td>$R_{dp}^*$</td>
<td>$R_{dp}/R_{dp}^*$</td>
</tr>
<tr>
<td>Chute rotating speed</td>
<td>$\omega$</td>
<td>$\omega^*$</td>
<td>$\omega = \omega_S$</td>
</tr>
<tr>
<td>Top gas velocity</td>
<td>$U$</td>
<td>$U^*$</td>
<td>$U^* / U_{ref} = U / U_{ref}$</td>
</tr>
</tbody>
</table>

![Fig. 3. The measurement of burden falling trajectory in the cold charging model.](image)

![Fig. 4. The measurement of the burden falling trajectory by crossed laser beam method in 5 800 m³ of Shasteel.](image)
the laser beams hit the outer and inner boundaries of the stream. Center positions of the outer and inner boundaries of the falling stream were marked in black dots as falling trajectories. After the falling trajectories of coke and ore measured in cold model times 15, they were compared with that measured in actual blast furnace and computed results. The measured trajectories of coke and ore in both the cold model and the actual blast furnace agree well with the computed results, see Fig. 5.

As known, the gas flow will affect the burden profile distribution in the radial direction of a blast furnace in three ways, fluidization of coke particle especially in the center part of blast furnace,\textsuperscript{13,14} collapse of coke surface\textsuperscript{17} and more importantly the decrease of deposit angle of burden materials.\textsuperscript{21,22} For this cold model, emphasis was placed on the decrease of deposit angle and the fluidization of coke particle. In previous study,\textsuperscript{21,22} $\theta/\theta_0$ was strongly affected by the $U/U_{mf}$ value, where, $\theta$ is the deposit angle of burden with gas flow, $\theta_0$ the deposit angle of burden without gas flow, $U$ the average gas velocity at furnace top, $U_{mf}$ the minimum fluidization velocity of burden. For this reason, the equal $U/U_{mf}$ was kept for both the actual blast furnace and cold model to get the top gas velocity $U^*$ for the cold model as shown in Eq. (7).\textsuperscript{23} In addition, from the measured results, coke particle is easier to get fluidized compared with ore, see Fig. 6, so, $U_{mf}$ calculation was based on the average particle size of coke for determination of blast flow rate injected to the cold model. The minimum fluidization velocity $U_{mf}$ was calculated at different particle sizes for coke and ore according to Eq. (7)\textsuperscript{24} and compared with the measured data shown in Fig. 6.

\[
U_{mf} = \frac{\phi g D_P \rho \varepsilon}{k_2 (1-\varepsilon)}
\]

Where, $D_P$: Mean size of particles, $\varepsilon$: Voidage fraction of packed bed (measured value: for coke, $\varepsilon=0.495$; for ore, $\varepsilon=0.375$), $\rho$: Apparent density of packed bed (for coke, $\rho=586$ kg/m$^3$; for ores, $\rho=2210$ kg/m$^3$), $\Phi$: Spherical factor of particles (for coke, $\Phi=0.63$; for ores, $\Phi=0.67$), $k_2$: gas resistance factor (for coke, $k_2=0.95$; for ore, $k_2=0.55$), which was measured by Yamada \textit{et al.}\textsuperscript{25}

\subsection{2.3. Experimental Method}

Mix the coke of different size groups as well as ore separately according to the weight ratio in Fig. 2, and put them into the top bunkers for coke and ore respectively. Start the blast blowing and charge the materials to the stock surface by a rotating chute at a controlled stock line and preset parameters such as flow control gate opening, blast volume and chute rotating speed, and charging pattern.

Consecutive coke and ore batches were charged alternatively into the cold model at the controlled stock line until the convergence of the stock surface. The measurement of burden surface height distribution was done for coke and ore respectively before and after dumping by a vertical ruler along a scale bar placed on top of the model furnace in the diametric direction, see Fig. 7(a). From measured results, the burden profile L1, L2 and L4 were gotten as shown in Fig. 7(a), assuming no change of coke layer thickness.
distribution during the descending of formed coke layer to the controlled stock line. While the after-collapse coke layer L3 was measured by a thickness meter which was made up of two steel rods connected by two wires to an Ohmmeter. Both the two rods were marked with scale and covered by Scotch tapes as insulator except the pointed tip end as in Fig. 7(b). One rod was pushed down from top surface of the ore layer to the coke layer as the measurement rod, the other kept still in coke layer as the still rod. As the measurement rod reaches the boundary of the ore layer and coke layer, there is an abrupt change of electric resistance, according to which, the coke and ore layer is defined as shown in Fig. 8(a). As the result, the ore layer thickness measured by thickness meter agrees well with the observed one shown in Fig. 8(b), proving the reliability of this thickness meter.

3. Experimental Results

As shown in Fig. 9, the coke and ore profiles at different U/Umf values were measured in the radial direction of the model furnace at the same O/C, stock line and charging pattern. U is the average top gas velocity, Umf the minimum fluidization gas velocity, r the distance from the sampling point to the center line of the model furnace, and r0 the radius of the model furnace throat. It has been found that the coke slit is rather narrow in the intermediate part around 3/8 to 3/4 of the throat radius, and when U/Umf is increased to 0.342, the coke collapse is remarkable, resulting in a much thinner coke slit in the intermediate part.

The effect of center coke amount set at the tilting position 12 with the smallest tilting angle, on the burden profile was also investigated. The center coke amount set for the charging pattern A and B is 19% and 16% respectively in weight portion. There is no center coke set for charging pattern C and D, but compared with D, the weight portion set at tilting position 8 was bigger for C, which means more coke towards center part. As results of the measurements, with the decrease of center coke amount, the pushed coke in the center part is increased, see Fig. 10(a). \( \Delta L_c \) is defined as the increased height of pushed coke represented by the hatched area in the center part of the model furnace due to the impact of charging ore. According to the formation energy theory about coke collapse, \( \Delta L_c \) can be quantitatively expressed by the formation energy of mixed layer \( E_M \) as defined by Eqs. (8) and (9).

\[
\Delta L_c = 3.49 \times 10^4 \times E_M - 136 \quad \quad \quad \quad \quad (8)
\]

\[
E_M = E_K + E_P = \frac{1}{2} MV^2 + MgH \quad \quad \quad \quad \quad (9)
\]

Where, \( E_M \): formation energy of mixed layer (kgm^2/sec^2), \( E_K \): collision energy of ore (kgm^2/sec^2), \( E_P \): potential energy of ore at falling point of ore (kgm^2/sec^2), M: charged mass of ore in one dump (kg), V: component of ore velocity in the direction of coke surface, H: vertical distance between falling point of ore and the coke surface at furnace center. From Eqs. (8) and (9), the change of height of pushed coke \( \Delta L_c \) has the same tendency with the change of collision energy of ore \( E_K \) and the change of potential energy \( E_P \), which can be used to explain the effect of center coke charging on the coke collapse phenomenon. Based on the observation results of starting time and ending time of coke collapsing during ore charging, 13rd turn of ore for start and 16th turn of ore for end, the potential energy of charging ore during the coke collapsing was calculated according to Eqs. (4) and (5). It is found that, with the decrease of center coke amount, the slope angle near the center part is increased, leading to deeper stock surface of coke layer and a larger potential energy of charging ore at falling point, as a result,

![Fig. 8.](image)

Measurement results by the thickness meter, a. The electric resistance change during the penetrating of the measurement rod into the burden layer, b. the comparison of measured ore layer thickness by thickness meter and the observed value.

![Fig. 9.](image)

a. Burden profile distributions at different U/Umf values, b. Measured coke layer thickness distribution after ore dump at different U/Umf values.
the increased coke layer thickness at the center part $\Delta L_c$ is increased, see Fig. 10(b).

As seen in Fig. 11, with the decrease of O/C at the same ore base $A \rightarrow B \rightarrow C \rightarrow D$, the thickness of the thin coke slit in the intermediate part significantly increases. The center coke column width is as high as 1/4 of the throat radius of the model furnace when the coke base is up to 14.35 kg in Fig. 11-D. The result verifies Kajiwara et al.'s argument that the coke base has a significant effect on the burden distribution. On the other hand, with the decrease of O/C at the same coke base $A \rightarrow B \rightarrow C \rightarrow D$ in Fig. 12, the width of the center coke column gradually increases, and the increased height of pushed coke $\Delta L_c$ decreases due to the smaller weight and collision energy of charging ore according to the formation energy theory, resulting in decrease of coke thickness in the center part, see Fig. 12.

When the stock line is increased from 1.2 m to 2.0 m, the pushed coke amount increases, see Fig. 13. This phenomenon can also be explained by the formation energy theory that, when the stock line is deeper, the charging ore has a higher velocity when it lands on the stock surface with larger collision energy, as the result, the height of pushed coke and the coke thickness at the furnace center is bigger.

The experiments A, B, C, D, E and F have been carried out to optimize the coke and ore layer distributions in the radial direction of the blast furnace, see Fig. 14. It is revealed that when the coke is rich in the center and peripheral parts of the furnace, the change of ore pattern has small effect on the coke thickness distribution, while after increasing the coke portion in the intermediate part and decreasing the coke portion in the wall and center part, the coke thickness in the intermediate part markedly improves as depicted in D, E and F in Fig. 14, with a concentrated strong center gas flow in a small area and a moderate gas flow at the wall side.

4. Discussion

4.1. Gas Fluctuation and the Center Flooding

How the burden layer is formed during the charging
process and how it affects the gas velocity distribution in the radial direction were also studied by an experiment, in which the burden profile and the gas distribution in the radial direction were measured after materials at each position were charged to the stock surface by a rotating distributor.

Figure 15 shows that almost all the coke at tilting positions 1 to 4 is piled at the corner of furnace wall, coke at position 5 to 8 mainly contributes to the thickness of coke layer in the intermediate part, and coke at position 12 dominates the coke thickness at the center part of the blast furnace. While ore at positions 1 to 3 mainly contributes to the thickness of ore layer in the peripheral part. Due to the coke pushing effect, a coke column is formed in the center part where strong gas flows through, preventing the charging ore from rolling downward to the center, which is the same with the result reported by Nishio et al.\(^{13}\) and the coke layer becomes thinner in the intermediate part of the model furnace.

As shown in Fig. 16, gas velocity distributions from A to G are measured after ore from tilting position 1 to 7 is dumped onto the coke layer. It has been found that the gas velocity at the interface of coke and ore layer is comparatively higher in the radial direction, and with the covering of charging ore on the coke layer, the gas velocity is gradually concentrated at the interface of center coke column and ore layer. Furthermore, the fluctuation of gas velocity has been also investigated by a measurement of air velocity at each radial point. For each measurement at a radial point, one second data within a period of 20 seconds was analyzed to get the average and standard deviation value. The standard deviation of air velocity is found to be proportional to the average value at each measurement point as shown in Fig. 17. From Figs. 16 and 17, it is thought that the maximum fluctuation of gas exists at the center-adjacent point where the interface of the center coke column and the ore layer is. Besides, radial throat gas temperature per second within one month was analyzed for Hongfa 2# blast furnace of Shasteel, where the charging philosophy for simultaneously developed center and peripheral gas flows was adopted. Temperature change per second, $\Delta T/\Delta t$ was compared in each sensor of the above-burden probe. From the analyzed results, it is obvious that the biggest fluctuation exists in E point which was thought to be the interface of the center coke column and the ore layer. This phenomenon agrees well with the experimental finding, see Fig. 18.
In addition to the gas flow fluctuation, it is also observed that small coke particles at the center coke column get fluidized at the center area of the model furnace which is the same with that reported by Jimenez et al. To study this phenomenon, the change of average coke particle size during coke discharging from top bunker, the average particle size distributions of coke and the average gas velocity distributions in the radial direction of the model furnace were also analyzed. It is shown in Fig. 19 that the lastly-discharged coke with comparatively smaller size is charged to the center part of the furnace and gets fluidized under strong center gas flow due to the small minimum fluidization gas velocity according to Fig. 6. And in the actual operation of 5800 m³ in Shasteel, flooding of the coke particle in the center area is also observed from the top camera. As seen in Fig. 20, the burning coke is splashing in a wide area of the center part of the operating blast furnace.

4.2. Thin Coke Slit and the Irregular Burden Descending

To quantify the effect of influencing factors on the thin coke slit in the intermediate part of the furnace, the factor of minimum coke slit $\kappa$ is defined as:

$$\kappa = \frac{T_{\text{min}}}{T_a}$$

(10)

where $T_{\text{min}}$ and $T_a$ represent the minimum coke slit and the average coke slit, respectively.

The factor of minimum coke slit $\kappa$ can be calculated using the following equation:

$$\kappa = \frac{T_{\text{min}}}{T_a}$$

(10)

where $T_{\text{min}}$ and $T_a$ represent the minimum coke slit and the average coke slit, respectively.

$$T_{\text{min}} = \text{Min}\{\text{average}(T_i, T_{i+1}, T_{i+2}) | (i = 0 \cdots 6)\}$$

(11)

$$T_a = \text{average}(T_0, T_1 \cdots T_6)$$

(12)
Hereinafter, the coke thickness means the thickness after coke collapse. $T_{\min}$ is the minimum value of the averaged coke thickness of 3 consecutive measurement points in the radial direction of the model furnace. $T_a$ is the average value of coke thickness at all measurement points in the radial direction.

The effect of $O/C$, $U/U_{mf}$ and the stock line can be quantified in Fig. 21, which shows that the minimum coke slit $\kappa$ value decreases with the increase of $O/C$, $U/U_{mf}$ and the stock line respectively. The influence of the charging pattern on the minimum coke slit $\kappa$ was also investigated in a quantitative way. Tilting positions from 5 to 8 and those from 4 to 7 are defined as the intermediate part for coke and ore respectively due to their larger contribution to the thickness in the intermediate part as discussed in section 3.1. The weight portion in the intermediate part for coke and ore at different charging patterns A to L were calculated and its effect on the minimum coke slit $\kappa$ was shown in Fig. 22.

It can be seen that, to increase the portion of coke in the intermediate part is the most effective way to increase $\kappa$ value, and to decrease the portion of ore in the intermediate part can also improve $\kappa$ value but the effect is much smaller compared with coke.

The burden descending velocity was calculated based on the 1 second data of mechanical sounding probe. During the normal descending of the probe, a sudden increase of descending velocity was considered as a slip. Descending velocity between 50 cm/s and 100 cm/s was taken as a small slip, between 100 cm/s and 200 cm/s as a large slip. The temperature change per second was calculated and analyzed based on the 1 second data of thermal couples placed at the center-adjacent part of the above-burden probe and at the 23.6 m level of the belly part. It is apparent that, when the typical charging pattern is changed by increasing the coke portion in the intermediate part and decreasing its portion on the wall side and in the center part, the thickness of the thin coke slit in the intermediate part is markedly increased, as a result, the fluctuation of gas flow is decreased and the slip number is reduced considerably as shown in Fig. 23. As known, permeability in the cohesive zone is determinant of the overall blast furnace permeability. It is speculated that after the locally-narrowed coke layer descends to the cohesive zone of the blast furnace, it inhibits the smooth gas flowing and causes the fluctuation of gas flow at the cohesive zone level, so the smooth burden descending cannot be secured during the normal operation.

5. Conclusion

The charging pattern setting for simultaneously-over-developed center and peripheral gas flow was preferred in Shasteel to achieve high production and withstand the unstable raw material quality, while this charging method lead to an unstable blast furnace operation. To comprehensively understand this phenomenon, a 1/15 cold model has been designed based on fundamental equations to keep the similarity between the actual blast furnace and the cold model. A couple of experiments were carried out and the results were analyzed combining with online operational data. The results obtained are described as follows:
The largest fluctuation in the radial direction at the interface between the center coke column and the ore layer.

(5) Small coke particles which lastly come out from the top bunker are charged to the center part of the blast furnace at the smallest tilting angle. These small size particles easily get fluidized at the center of the blast furnace with a large coke column.

Acknowledgement

The authors are indebted to Mr. Taguchi, who worked in Shasteel as the manager in ironmaking & Environment Research Group from 2008 to 2013, and Mr. Marushima, who worked in Shasteel as technical advisor from 2009 to 2012, for their helpful advices.

REFERENCES


(1) This charging pattern setting leads to a thin coke slit in the intermediate part of the blast furnace throat. With a higher blast flow rate, a higher O/C and a deeper stock line, the coke slit gets much thinner in the intermediate part with the existence of coke collapse.

(2) Under the charging pattern of excessive coke set for both the center and peripheral parts, to increase the portion of coke in the intermediate part is the most effective way to increase $\kappa$ value, and to decrease the portion of ore in the intermediate part can also increase $\kappa$ value but the effect is much smaller compared with coke.

(3) Coke layer with a thin coke slit in the intermediate part will cause the gas flow fluctuation at the cohesive zone level and unstable burden descending.

(4) Excessive amount of coke charged to the center part of the furnace leads to a wide center coke column and