1. Introduction

It has been well known that the ratio of ore to coke layer thickness and particle size distribution in the radial direction are two key factors of burden distribution control in the blast furnace. The former has greatly improved the operational results of blast furnace through not only hardware development such as charging equipment and profilemeter, but also software such as charging mode, nut coke and center coke charging in the past three decades. On the other hand, the latter has been relatively less investigated than the former. This means that mainly the type of charging equipment fixes the radial particle size distribution. Storage bin, surge hopper and top bunker used in the blast furnace are almost funnel flow typed bunkers. In the funnel flow bunker a bulk solid flows in a channel formed within stagnant solid. During flowing without charging, flow of burden in a funnel flow bunker starts from the right above layer of the outlet, and moves gradually to the wall part. Therefore, it has been well known that the time serial particle size change during flow is determined by the radial particle size distribution in burden flow bunker, and consequently fixes the radial particle size distribution in the blast furnace.

The previous researches were mainly carried out to find out the relation of the internal structure of bunker with the time serial particle size distribution according to either the experiments, or the kinematical model. However, it has not been studied on the flow mechanism in funnel flow bunker.

Jenike and Takahashi et al. calculated the boundary between dead zone and flow zone based on the method of characteristics. They considered that the boundary between dead zone and flow zone is identical with the slip line in the perfectly rigid plastic model. Therefore, the angle between the vertical line and the slip line might be considerable to result in funnel flow. Also using the perfectly rigid plastic model, Arnold et al. calculated the stresses at the wall of funnel flow bunker analytically through modifying Jenike's model and Walter's model. However, it has been known that because the perfectly rigid plastic model provides no information on the state of stress and deformation before the yield condition is reached, it can not be applied to the funnel flow or plug flow mode. Therefore, predicting wall stresses in this type of storage structure is more difficult and often unsatisfactory.

In this study, the solid flow in top bunker of the blast furnace through Walters' model using the method of differential slice was approximately discussed. Consequently it was found that the solid flow in a funnel flow bunker transferred from the initial plug flow to the final funnel flow. Moreover, through modifying the shape of burden deposit in the top bunker to change the radial particle size distribution in the blast furnace, the burden descending could be stabilized by maintaining central gas flow.

2. Theoretical Analysis on the Solid Flow in a Funnel Flow Bunker

2.1. The Characteristics of Discharge Behavior of Burden in a Top Bunker

With regard to the converging hopper, Jenike showed...
that the bounds between mass flow and funnel flow is given by

\[ \alpha = \frac{\pi}{2} - \frac{1}{2} \cos^{-1} \left[ \frac{1-\sin \delta}{2 \sin \delta} \right] \beta \] ..................(1)

\[ 2\beta = \phi + \sin^{-1} \left( \frac{\sin \phi}{\sin \delta} \right) \] ..................(2)

where \( \delta \) is internal friction angle, \( \phi \) is wall friction angle, \( \beta \) is angle between major principal stress and normal to hopper wall, and \( \alpha \) is half angle of hopper.

Table 1 shows the physical properties of burden measured by Jenike shear tester, and the criterion angle between mass flow and funnel flow in general. Top bunkers with half angle of about 55° to 60° are used in the blast furnace. Half angle means the angle between the vertical line and the slope line of bunker. Hence top bunkers might be funnel flow as estimated according to Eq. (1).

Figures 1 and 2 show the discharge behavior observed through acrylic plate in a center feed bunker with half angle of 55° and a parallel bunker with half angle of 60° which were made from the steel plate. White color painted sinter were used as charge material, and coke as line tracer. Discharge rate was determined based on scale factor. Both figures were obtained by videotaping the discharge behavior, and by capturing the freeze-image. In the initial stage of discharge, plug flow, in which the boundary line between flow region and stagnant region is almost vertical, occurred at the central region just above the outlet, and formed a flow channel. The width of flow channel increased with discharge, and the upper free surface approached to the wall to maintain the constant angle less than the repose one. From the middle stage of discharge, the type of flow changed to the funnel flow. Except that the centerline of flow channel did not correspond to that of parallel bunker, this discharge pattern was almost the same irrespectively of bunker type.

Jenike\(^9\) showed that the angle of flow channel is governed only by the internal friction angle of the solid. By contrast, Tüzun \textit{et al.}\(^{14}\) showed that the slope angle is decided by the internal and wall friction angles. Moreover, it was represented that in the discharge experiments by Michalowski\(^{15}\) on plane parallel and converging bunker the angle of boundary line between flow zone and stagnant one was almost vertical. However, in Fig. 1, this study showed that the angle of boundary between flow zone and stagnant one changed consecutively with the discharge step as follows.

i) Diverging in the initial stage,
ii) Vertical in the middle stage,
iii) Converging in the final stage.

These results agree with Benink’s analysis\(^{16}\) that besides mass flow and funnel flow a third type of flow, as it is called an intermediate flow, exists during discharge.

2.2. Approximate Analysis on the Behavior of Plug Flow in the Initial Stage of Discharge

In this study, the method of differential slices proposed by Walker\(^7\) and Walters\(^5\) was used to predict the stresses in flow and stagnant region in a funnel flow bunker. It was assumed that the flow channel at the initial stage of discharge is similar to a cylinder based on Figs. 1 and 2, and that vertical stress in the flow channel is constant in the radial direction. Figure 3(a) shows the force balance in differential slices. Following Walters, we could obtain a differential equation.

\[ \frac{d \bar{\sigma}}{dz} + \frac{4 (\tau_w)}{d} = \rho g \] ..................(3)

where \( \bar{\sigma} \) is mean vertical stress, \( (\tau_w) \) is vertical shear stress at the wall, \( d \) is diameter of vertically sided section of bunker, \( \rho \) is bulk density of solid, and \( g \) is gravity acceleration.

Because it was assumed that the vertical stress is constant, the vertical stress at the wall \( (\sigma_w) \) is

\[ (\sigma_w) = \sigma_z \] ..................(4)

Figure 3(b) shows the relation among the stresses in flow and stagnant region.

\[ (\tau_w) = \sigma_x \tan \delta \] ..................(5)

\[ \sigma_x = \frac{x}{\sin \delta} \] ..................(6)

\[ (\bar{\sigma}_z) = \frac{x}{\sin \delta} \] ..................(7)

Combining Eqs. (5), (6), and (7),

\[ (\tau_w) = \frac{(1+\sin \delta)}{(1-\sin \delta)} \tan \delta (\sigma_z) \] ..................(8)
Substituting Eq. (8) for \((\tau_z)_w\) in Eq. (3),

\[
\frac{d\sigma_z}{dz} + 4B\sigma_z = \rho g \tag{9}
\]

\[
B = \frac{(1+\sin \delta)}{(1-\sin \delta)} \tan \delta \tag{10}
\]

Integrating Eq. (9) on condition that we put \(\sigma_z = 0\) at \(z = z_0\),

\[
\sigma_z = \frac{\rho gd}{4B}(1-e^{-4Bz/d}) \tag{11}
\]

We can use Eqs. (4), (6), (7) and (11) to calculate the horizontal stress in flow and stagnant region.

\[
\sigma_r = \frac{\rho gd}{4 \tan \delta}(1-e^{-4Bz/d}) \tag{12}
\]

Meanwhile the vertical stress in the stagnant region can be estimated by Janssen’s equation\(^{18}\)

\[
\sigma_v = \frac{\rho g R}{K_1 \tan \phi}(1-e^{-K_1 z \tan \phi / R}) \tag{13}
\]

where \(K_1\) is constant, and \(R\) is hydraulic radius.

\[
R = d/4 \tag{14}
\]

**Figure 4** shows the calculated stress distribution in flow and stagnant region. In stagnant region the vertical stress is larger than the horizontal stress resulting in an active stress state. By contrast, in flow region it is reversed in a passive state. Under this stress distribution, lines of major principal stress of burden in a top bunker, as shown in **Fig. 5**.

\[
2\varepsilon_1 = \frac{\pi}{2} + \phi + \sin^{-1}\left(\frac{\sin \phi}{\sin \delta}\right) \tag{15}
\]

\[
2\varepsilon_2 = \frac{\pi}{2} + \phi - \sin^{-1}\left(\frac{\sin \phi}{\sin \delta}\right) \tag{16}
\]
\[ \phi_s = \tan^{-1}(\sin \delta) \] ............................(17)

where \( \varepsilon \) is angle between the major principal stress and the horizontal, \( \phi_s \) is slope friction angle, \( \delta \) and suffix 1 and 2 mean active and passive states.

Figures 4 and 5 show how plug flow occurs at the initial stage of discharge. Figure 4 shows that stagnant region is in the active stress state even during discharging because the coefficient of earth pressure is less than one. Therefore, line of the main principal stress in stagnant region makes an acute angle of 73° to 75° with the horizontal line as shown in Fig. 5. Terzaghi\(^{19}\) represented that when the initial state of elastic equilibrium is changed into a state of plastic equilibrium to result in an active failure, the angle between the shear line and line of the main principal stress (\( \alpha \)) is

\[ \alpha = \frac{\pi}{4} - \frac{\delta}{2} \] ............................(18)

\( \alpha \) for sinter and coke used in this study was in the range of 22.5° to 25°. So it could be estimated that the shear line, or the interface line between stagnant and flow region made an angle of 5.5° to 10° with the vertical line. By contrast, Benink\(^{16}\) reported that when the particles with internal friction angle of 40 to 45 form a funnel flow, the slope angle of flow region is in 18° to 21°. This means that in the initial stage of discharge the angle between the shear and the vertical line is only half of the slope angle of flow region in funnel flow to result in plug flow according to the classification of flow pattern by Drescher\(^{15}\) and Michalowski.\(^{15}\) They distinguished plug flow from funnel flow according to the slope angle of flow region as well as the shape of stagnant region.

Transferring from plug flow to funnel flow in the top bunker of blast furnace, it could be predicted that the time serial particle size change during discharging from a top bunker was determined by the radial particle size distribution of burden deposited in top bunker.

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3. The Experimental

A simulator under the similarities of charging system was made based on the scale factor of 1/12 to Pohang No. 1 blast furnace. The discharging behavior of particles from lower bunker and the particle size distribution in the radial direction of furnace were dealt with. Center feed bunker with or without stone box was used to confirm the effect of the interior structure of bunker on time serial particle size change during discharging from the lower bunker and the particle size distribution in the radial direction of furnace top.

Ore and coke size ranges were 0.5–4.75 mm and 2–6.35 mm respectively, and the particle size distribution was shown in Table 2.

For the time serial checking of the particle size from storage bins to the furnace, samples were taken from surge hopper to the lower bunker. In order to relate the particle size distribution in the top bunker to that in the furnace, particles were sampled from the upper and lower bunkers. After charging one batch consisting of coke and sinter, all of the particles deposited on the top layer were sampled by vacuum cleaner for the size distribution analysis. Then magnetic separator was used to separate coke from sinter among particles sampled from the interface between coke and sinter layer.

Figure 6 shows the schematic diagram of 1/12 scale model used in this study. The charge weight was controlled by load cell attached to a weighing hopper. The surge hopper could be moved over the upper bunker by a skip. An elevator set under the furnace bottom maintained the stock

| Size(mm) | 0.5 | 1   | 1.5 | 2   | 2.4 | 3.36 | 4.75 | 5.35 | 6.35 |
|---------|-----|-----|-----|-----|-----|------|------|------|------|
| Ore     | 3.1 | 23.0| 16.0| 17.3| 22.7| 15.0 | 2.9  |      |      |
| Coke    | 4.2 | 43.7| 44.8| 7.1 |      |      |      |      |      |

Table 2. Particle size distribution used in this study. (wt%)
leve of burden.

4. Results and Discussions

4.1. The Time Serial Change of Particle Size Distribution from the Surge Hopper to the Lower Bunker

Figure 7 shows relative particle size distribution of ore during discharging from surge hopper. The figure shows the typical particle size distribution that could be predicted the phenomena in a funnel flow bunker. The surge hopper used in this study had the type of pyramidal hopper plus vertical section instead of conical hopper plus vertical cylinder. However, discharging pattern was similar to that of the parallel bunker shown in Fig. 2. The particles, falling down from the belt conveyor, were deposited to form a hill in which apex is near the centerline of the surge hopper. According to the natural segregation taking place along the slope, small particles were deposited on the center part, but large ones on the wall part. This layer structure resulted in the discharging behavior shown in Fig. 7 in association with discharge pattern as shown in Fig. 2. The above particle size distribution of ore during discharging from the surge hopper was not changed with the discharge rate in the range of 54 to 130% of standard value (1.27 kg/sec).

Figure 8 represents particle size distribution of ore in the upper bunker. It showed two characteristics. Firstly the particle size at the lower part was smaller than that at the upper part of burden layer. This was due to the time serial particle size change during discharging from the surge hopper as shown in Fig. 7. Secondly the particle size at the wall part (dimensionless radius 1 or -1) was larger than that at the center part (dimensionless radius 0) regardless of the vertical height. Also this pattern was not almost changed with charging rate of ore into the upper bunker. This particle size distribution of ore in the vertical direction of the upper bunker corresponded well to the discharging behavior shown in Fig. 7. The radial distribution resulted from the natural segregation along the slope of burden layer, and the apex of burden layer did not coincide with the centerline of the upper bunker so that the particle size difference was shown in both sides.

Figure 9 shows the particle size distributions of ore in the lower bunker of scale model and actual blast furnace. According to the experimental result in scale model, the particle size distribution in the lower bunker was greatly different from that in the upper bunker. Considering the big segregation in the vertical and radial directions of the upper bunker, the figure shows distinctly that the difference of particle size in the vertical direction decreased from 50% in the upper bunker to 16% in the lower bunker, and that particle size distribution changed inconsistently in the vertical and radial directions as compared with the consistent change in the upper bunker. In order to analyze the reason why the big difference of particle size in the vertical direction of both bunkers occurred, the time serial particle size change during discharging from the upper bunker was...
checked. As results, it was found out that the shape of the time serial particle size change was different from that from the surge hopper, and that the difference of relative particle size between the initial and final discharge stage decreased greatly compared with that at the surge hopper. Also in order to confirm whether the particle size distribution in the lower bunker of scale model reappeared in the lower bunker of actual blast furnace or not, ore particles were sampled in the two directions shown in Fig. 9. According to the analysis result, the following two peculiarities appeared. Firstly the particle size was bigger at the central part rather than at the wall part as opposed to the normal case. It was ascertained that the stone box, set up for protection of material control gate, caused such an abnormal particle size distribution in the lower bunker. Four apices of burden by the stone box and its support cross beam were formed at half radius point of the bunker as shown in Fig. 10(a), and brought about the particular segregation in which large particles flowed into the center part because the slope of burden could not grow toward the wall part enough to secure big particles there. Therefore, it was thought that the particle size distribution in the bunker with a stone box depended on the dimension of bunker. If the diameter of bunker was large enough to limit the apex site of burden within half radius, particle size would be bigger at the wall part rather than at the center part. Finally particle size distribution was almost the same both in the apex and valley directions.

Considering the plug flow and particular particle size distribution in the lower bunker, it was expected that small sized blast furnace with center feed bunker equipped with stone box might have an extraordinary time serial particle size change during discharging from the lower bunker.

4.2. Reconstruction of the Lower Bunker
Figure 10 shows the schematic diagram for rebuilding the interior structure of the lower bunker. In order to achieve the normal particle size distribution in the lower bunker, it was designed to attach a central chute around the stone box that could change the shape of burden layer from M to inverted-V. The following two points must be considered in designing: i) to keep the opening area enough to avoid a bridge, ii) to choose the proper height over the cross beam not to jump over particles collide with the stone box. Through adjusting the shape of burden layer by reconstruction of the lower bunker, it was possible to obtain the normal particle size distribution in which large particles deposited on the wall part, while small ones on the center part.

4.3. Discharging Behavior from the Lower Bunker and Particles Size Distribution in the Furnace
Figure 11 shows the time serial particle size distribution of ore during discharging from the lower bunker with/without the central chute around the stone box. As predicted from Fig. 9 in case of the stone box without central chute, the particle size discharged from the bunker at later stage turned out smaller, which brought about the smallest particle size distribution at center part according to spiral charging. On the contrary, in case of the stone box with central chute, the time serial particle size change represented a sinusoidalpattern that large particles discharged at later stage. This figure confirms that the method of adjusting the particle size distribution in the lower bunker through the shape of burden layer by the central chute was efficient.

Figure 12 shows the radial particle size distribution of ore in furnace. In case of the stone box without central
chute, the particle size was smallest at the center part. Consequently it was confirmed that this abnormal particle size distribution had brought about the weak central gas flow. However, owing to the central chute, the radial particle size distribution was recovered to normal pattern.

4.4. Improvement of the Gas Flow

Figure 13 represents temperature profile measured by the shaft sonde in a small sized blast furnace with center feed bunkers. It had experienced the weak central gas flow before the lower bunker was rebuilded. Takeda et al. reported that the weak central gas flow could be caused by huge flow of ore into the center part according to ore layer collapse. However, because impact energy on ore charging in the small blast furnace was weaker compared with big one, it was believed that the weak central gas flow was due to the abnormal particle size distribution as shown in Fig. 12. This assumption was proved by the fact that after the radial particle size distribution in furnace had been changed, the gas flow pattern was reversed in the radial direction.

5. Conclusion

Flow mechanism of solid in bunkers used in the iron-making works was approximately analyzed by the method of differential slice, and the time serial particle size change in the blast furnace with center feed bunkers was investigated from the surge hopper to the furnace using the 1/12 scale model. The following results were obtained.

(1) During discharging from the top bunker, the flow pattern of burden was changed from plug flow at the initial stage to funnel flow after the middle stage.

(2) According to the approximate stress analysis, the flow region could be separated from the stagnant region by the ratio of horizontal to vertical stress.

(3) The particle size distribution in the lower bunker was influenced by not only the time serial change from the storage bin to the upper bunker, but also the interior structure and the distance of apex of burden from the center line of the lower bunker.

(4) It was proved that rebuilding the interior structure of the lower bunker could fundamentally modify the radial particle size distribution, which was strongly related to gas flow.

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