Advanced Supporting System for Burden Distribution Control at Blast Furnace Top

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Burden distribution control is one of main technologies to keep the good permeability and the high reaction efficiency in a blast furnace. However, in actual blast furnace operation, there are variations in burden distribution due to various factors, such as fluctuations in condition of the raw materials, fluctuations of the mechanical properties of charging devices, the changes of charging devices due to abrasion and so forth. Such variations could be a negative factor to conduct blast furnace operation in high productivity and low reducing agent rate. The advanced supporting system for burden distribution control at blast furnace top regards those variational factors as the characteristic parameters of burden distribution formation through analyzing on-line monitoring probe data to make effective supports for a proper burden distribution control. In this paper, the composition of the supporting system and the results of applying this system to actual blast furnace are described.

KEY WORDS: ironmaking; blast furnace; burden distribution control; supporting system; bunker model; burden distribution model.

1. Introduction

In blast furnace operation, burden distribution is one of main items to be appropriately controlled in order to keep the good permeability and the high reaction efficiency. Thus, many efforts have been made in the study of the formation behavior of the burden distribution. The burden distribution models^{1–4)} based on model experiments have been developed and been applying to blast furnace operation.

However, in actual furnace operation, there are cases in which deviations between an action target and the result, or variations in burden distribution were occasionally found. **Figure 1** shows an example of variations in the gas utilization distribution under the same charging condition. These phenomena are supposed to be induced by various factors, such as fluctuations in condition of the raw materials, fluctuations of the mechanical properties of charging devices, the changes of charging devices due to abrasion and so forth. Though such phenomena could be a large factor that depresses the productivity and influence the reducing agent rate, it is too difficult to get the precise and entire information about them and take them into account deductively in burden distribution control.

Therefore, it could be a key technology in making effective supports for a proper burden distribution control to develop the method for taking the effects of those variational factors into account. This work aims at this point, and regards the effects as the characteristic parameters of burden distribution formation through analyzing on-line monitoring probe data, such as shaft gas probe, to realize the high

performance supports.

The supporting systems^{5–9)} of the burden distribution control using artificial intelligence (AI) or neural network, which are based on correlation of earlier data of its own blast furnace operation, have also developed. However, they are not models based on physical phenomena as well as regardless of the variational factors' effects, so that they are not supposed to be capable to effective supports for a proper burden distribution control.

In this paper, the supporting system for burden distribution control at blast furnace top equipped with bell-less charging device is described, then, the application results to the blast furnace operation and discussion about characteristics in burden distribution behavior of an actual furnace.

Fig. 1. Variations of the gas utilization distribution.

2. Advanced Supporting System for Burden Distribution Control

2.1. Outline of the System

2.1.1. Composition of the System

Figure 2 shows the component of the advanced supporting system for burden distribution control. The system is composed of the 3-dimensional bunker model, the burden distribution model and the postprocessing. The 3-dimensional bunker model calculates behavior of burden discharge in size distribution and sort of burden from a bunker as a function of time. The burden distribution model calculates the radial distribution in ore/coke, size distribution and so on. While the burden distribution model calculates in terms of radial distribution of burden, the radial distribution of gas velocity, gas utilization are calculated in the postprocessing based on the results of burden distribution model.

2.1.2. Data Flow of the System

The system has two modes: (1) auto-analysis mode and (2) future prediction mode. Data flow in each mode is shown in Fig. 3.

(1) Auto-analysis Mode

The auto-analysis mode of the system provides analyzed

Fig. 2. Component of the advanced supporting system for burden distribution control.

results of burden distribution including variations by taking the effects as the characteristic parameters of burden distribution formation through analyzing on-line monitoring probe. The input of the system in this mode is operational (charging and blast) conditions and measured information through on-line monitoring probe data, gas utilization distribution obtained by shaft gas probe. The system in this mode determines some parameters in the formation of burden distribution, such as coke collapse, penetration of ore into coke layer and size segregation of burden, to minimize the error defined by the following equation by use of Marquart method which is a kind of nonlinear least squares analysis method.

$$\varepsilon = \sum_{i=1}^n \left| (\eta_{CO})_i - \frac{y_{CO,i}^{top}}{y_{CO,i}^{top} + y_{CO_2,i}^{top}} \right| \dots \dots \dots (1)$$

where $y_{CO,i}^{top}$, $y_{CO_2,i}^{top}$ are the top gas composition of CO, CO₂ measured through shaft gas probe and $(\eta_{CO})_i$ is the calculated gas utilization in the i -th radial zone, respectively, and n is the number of mesh division in the radial direction.

Therefore, the output of the system in this mode is model parameters as analyzed result in addition to state of burden distribution.

(2) Future Prediction Mode

The future prediction mode of the system provides prediction of burden distribution, when changing charging conditions, by use of parameters analyzed in the auto-analysis mode. The input of the system in this mode is operational (charging and blast) conditions and model parameters analyzed in the auto-analysis mode. The output of the system in this mode is prediction result of burden distribution.

As described above, the system has the brand-new and advanced functions of analysis and prediction of burden distribution including variations in actual blast furnace by use of on-line monitoring probe data.

2.2. 3-Dimensional Bunker Model

The input of the 3-dimensional bunker model is the charging conditions that are the amount and size distribution of each sort of burden and their order of burden charge into the bunker from charging belt conveyor. And the output of this model is discharging behavior, that is, the transi-

Fig. 3. Data flow of the advanced supporting system for burden distribution control.

tion of the particle size and amount ratio of each sort discharged from bunker.

The size distribution of the burden in the bunker before discharge is determined by the method of Kondo *et al.*,¹⁰⁾ which can be described as follows:

$$\frac{dX_n}{dl} = -\alpha X_n(1-X_n) \dots\dots\dots(2)$$

where X_n is cumulative under size, l is the distance from falling point (m) and α is the coefficient of size segregation (1/m). Integrating Eq. (2), following equation can be obtained:

$$\ln \frac{X_n}{1-X_n} = -\alpha l + \beta \dots\dots\dots(3)$$

Here, α , which depends on burden sort and physical conditions of charge, is determined by sieving measurement of the size of the samples in the bunker and β is determined by mass balance of each particle size of the stacked burden.

The discharging behavior of the bunker can be expressed by three parameters. The one is the angle of stacked burden (θ_{b1}) in the bunker. It is determined by burden profile measurement in the bunker. The two other parameters are the angle of rat-hole (θ_{b2}) and the angle of collapse (θ_{b3}) as shown in Fig. 4. They are determined by the transition of size and sort of discharging burden. The order of discharge in this model is decided as the number written in Fig. 4.

2.3. Burden distribution model

The input of the burden distribution model is the charging conditions that is the output of the 3-dimensional bunker model and conditions concerning distributing chute. The outputs of this model are radial burden surface profile and distribution of amount ratio of ore to coke (ore/coke), size distribution.

Following physical phenomena are taken into account in the model: (1) falling trajectory of burden, (2) size segregation of burden, (3) coke collapse, (4) penetration of ore into coke near center region. These items are briefly described below.

2.3.1. Falling Trajectory of Burden

Falling trajectory of burden is calculated by solving equation of motion of a single particle with the assumption of no interaction between particles.³⁾ The equation of motion is divided into two regions, *i.e.*, the region on the dis-

Fig. 4. Parameters for discharge of burden in 3-dimensional bunker model.

tributing chute and the region under the distributing chute. On the distributing chute, centrifugal force, Coriolis force, friction force and gravity force are taken into account. Under the distributing chute, free fall is calculated with the initial condition that is calculated results at the end of the distributing chute.

2.3.2. Size Segregation of Burden

The same manner as the 3-dimensional bunker model is applied.

2.3.3. Coke Collapse

Coke layer collapses when ore is charged as shown in Fig. 5. According to Inada *et al.*,³⁾ extent of mixed layer formation can be linearly expressed by “formation energy of mixed layer”, E_M as follows:

$$\Delta L_C = 3.49 \times 10^{-4} \times E_M - 136 \dots\dots\dots(4)$$

Here, “formation energy of mixed layer” is defined as the following expression:

$$E_M = E_K + E_P = \sum_{i=n_1}^{n_2} \frac{1}{2} m_i v_i^2 + m_i g H_i \dots\dots\dots(5)$$

where,

E_K : collision energy of ore (J)

E_P : potential energy of ore at falling position of ore (J)

m : charged mass of ore velocity at i -th turn (kg)

v_i : component of ore velocity in the direction coke surface at i -th turn (m/s)

H_i : vertical distance between falling position of ore and the burden surface at lowest surface at i -th turn (m)

n_1, n_2 : starting and finishing turn of the mixed layer formation, respectively (—)

However, Eq. (4) cannot be applied to the ore charging onto coke terrace because coke collapse does not occur. To solve this problem, in the case of charging onto coke terrace, the model employs stability theory of slope. In this theory, the factor of safety is defined as the ratio between the shear strength of the material and the shear stress developed along the potential failure surface as follows:

$$\text{Factor of safety} = \frac{\text{shear strength of the granular material}}{\left(\frac{\text{shear stress developed along the potential failure surface}}{\right)} \dots\dots\dots(6)$$

If the factor of safety is greater than 1, the collapse does

Fig. 5. Layer structure after charging ore onto coke layer.

not occur. The model searches the surface that gives the minimum value of the factor of safety and decides the implement of coke collapse.

2.3.4. Penetration of Ore into Coke Near Center Region

Nowadays, the burden distribution has been oriented to enhancing the gas flow in the center region for a stable operation, and fluidization near center is frequently observed. The layer structure, the formation process of it and amount of stacked ore in the center region are affected due to fluidization near center as shown in Fig. 5. Therefore, full-scale model experiment was conducted to quantify the amount of penetrated ore into fluidizing coke region.

Figure 6 shows the experimental apparatus of bell-less charge at a full scale. The container is rectangular parallelepiped, 5.4 m of the length corresponds to the radius of the blast furnace, and the width is 1.0 m. The air is supplied from the bottom of the apparatus off which is partitioned into six sections to independently control the gas flow rate in the radial direction. The cross section of the layer structure and the formation process of it are observable through an acrylic board. The velocity of burden particles at the end of the distributing chute is adjusted to be equal to that of the actual blast furnace.

In the experiment, the base coke layer that is based on the measurement in blast furnace operation was initially formed. The gas velocity near center where is less than 0.17 in dimensionless radius was set to be slightly greater than minimum fluidization velocity, and the gas velocity other than near center was set to be the same pressure gradient as actual blast furnace.

Then, 300 kg of ore that corresponds to a single ring of charge by distributing chute of blast furnace was charged two times on the base coke layer. After charging the ore, fluidization stopped. Finally, all burdens were sampled in each section, and the amount of ore and coke was measured.

Figure 7 shows the effect of the falling position of ore on the amount of stacked ore near the center (Dimensionless radius < 0.185) by changing the tilting angle of the distributing chute. The amount of stacked ore near the center increases with shifting the falling position of ore in the direction of center. Fluidization enhances the amount of the ore

Fig. 6. Experimental apparatus.

penetrated into the base coke bed near the center.

Figure 8 shows the penetrated depth of ore into coke layer near the center that is obtained by transforming above result of the difference between with fluidization and without gas flow. The penetrated depth of ore into coke layer near the center linearly increases with increasing amount of stacked ore near the center without gas flow. The correlation equation of the experimental result can be written as follows:

$$h_{\text{ore}} = 6.86 \times 10^{-4} W_{\text{nb}} \dots\dots\dots (7)$$

whrre h_{ore} is the penetrated depth of ore into coke layer near the center (m) and W_{nb} is the amount of stacked ore near the center without gas flow (kg/m^2).

2.4. Postprocessing in the System

2.4.1. Gas Velocity Distribution³⁾

Assuming that there is no cross-flow, gas velocity distribution is determined to be the same pressure gradient in the radial direction. The gas pressure gradient is calculated by Ergun's equation.

2.4.2. Gas Utilization Distribution

Gas utilization distribution can be calculated by taking the material balance between top gas and bosh gas into account with assumption of no cross-flow as follows:

$$(\eta_{\text{CO}})_i = \frac{(W_{\text{O}}/F)_i \cdot X_{\text{O}} \cdot \frac{22.4}{16} (1 - \gamma_{\text{Ci}} - \gamma_{\text{Hi}})}{\gamma_{\text{Ci}} \cdot (W_{\text{O}}/F)_i \cdot X_{\text{O}} \cdot \frac{22.4}{16} (1 - y_{\text{CO}}^{\text{bosh}}) + y_{\text{CO}}^{\text{bosh}}} \dots (8)$$

Fig. 7. Effect of falling position of ore on the amount of stacked ore near the center.

Fig. 8. Relationship between amount of stacked ore without gas flow and penetrated depth of ore into coke layer near the center.

Here, $(W_O/F)_i$ is the rate of the ore amount to the gas volume in the i -th radial zone and expressed by

$$(W_O/F)_i = U_{Si} \frac{L_{Oi}}{L_{Oi} + L_{Ci}} \rho_O / V_{gi} \dots\dots\dots(9)$$

X_O : ratio of oxygen as iron oxide in iron ore (-)

U_{Si} : descending velocity of burden in the i -th radial zone (m/s)

L_{Oi}, L_{Ci} : thickness of ore layer and coke layer in the i -th radial zone, respectively (m)

ρ_O : bulk density of ore layer (kg/m^3)

V_{gi} : gas velocity in the i -th radial zone (m/s)

γ_{Ci}, γ_{Hi} is the ratio of direct and hydrogen reduction, respectively, and can be calculated with measured top gas composition obtained by shaft gas probe as follows:

$$\gamma_{Ci} = \frac{y_{COi}^{\text{top}} + y_{CO_2i}^{\text{top}} - \frac{y_{N_2i}^{\text{top}}}{y_{N_2}^{\text{bosh}}} y_{CO}^{\text{bosh}}}{y_{COi}^{\text{top}} + 2y_{CO_2i}^{\text{top}} + y_{H_2Oi}^{\text{top}} - \frac{y_{N_2i}^{\text{top}}}{y_{N_2}^{\text{bosh}}} y_{CO}^{\text{bosh}}} \dots\dots\dots(10)$$

$$\gamma_{Hi} = \frac{y_{H_2Oi}^{\text{top}}}{y_{COi}^{\text{top}} + 2y_{CO_2i}^{\text{top}} + y_{H_2Oi}^{\text{top}} - \frac{y_{N_2i}^{\text{top}}}{y_{N_2}^{\text{bosh}}} y_{CO}^{\text{bosh}}} \dots\dots\dots(11)$$

where $y_{COi}^{\text{top}}, y_{CO_2i}^{\text{top}}, y_{H_2i}^{\text{top}}$ and $y_{H_2Oi}^{\text{top}}$ are the top gas composition of CO, CO₂, H₂ and H₂O in the i -th radial zone, respectively. $y_{H_2Oi}^{\text{top}}$ can be calculated by

$$y_{H_2Oi}^{\text{top}} = \frac{y_{N_2i}^{\text{top}}}{y_{N_2}^{\text{bosh}}} y_{H_2}^{\text{bosh}} - y_{H_2}^{\text{top}} \dots\dots\dots(12)$$

$y_{CO}^{\text{bosh}}, y_{CO_2}^{\text{bosh}}, y_{H_2}^{\text{bosh}}$ are the bosh gas composition of CO, CO₂ and H₂, respectively.

3. Example of Calculation Using Supporting System

3.1. Auto-analysis Mode

The auto-analysis was performed on Kashima No. 2 blast furnace. Examples of result of the auto-analysis mode, the layer structure, the ratio distribution of the ore amount to the coke amount (ore/coke), the size distribution of the burden and the distribution of the gas utilization, are shown in **Fig. 9**. The calculated result of the gas utilization distribution shows good agreement with the measured result of that.

Figure 10 shows the transition of the gas utilization near the center. The gas utilization near the center fluctuated, regardless of change of charging conditions, and has a different base level in each period due to unknown factor. The amount of penetrated ore near the center was analyzed by comparing with the result of the model experiment as shown in **Fig. 11**. Since the results of the auto-analysis are positioned near the same line in each period, it is supposed to be possible to predict the burden distribution in the near future by use of the parameters analyzed in this mode even

Fig. 9. Example of result of the auto-analysis mode.

Fig. 10. Transition of gas utilization near center (dimension radius: 0.24).

Fig. 11. Results of the system in auto-analysis mode on the penetrated depth of ore into fluidizing coke layer near the center.

though the burden distribution contains variations due to unknown factors.

3.2. Future Prediction Mode

The length of the coke terrace was decreased by changing the condition of burden charge in order to improve permeability in the blast furnace by promotion of the size segregation of the burden. The results in the future prediction mode in the period are shown in **Fig. 12**. They are based on the parameters analyzed in the auto-analysis mode just before changing the length of the terrace. The tendency of the amount of the collapsed coke agrees with the result in the auto-analysis mode that was continued after changing the conditions. And the tendency of the result of the shaft permeability in the future prediction mode agrees with the measured values. Thus, it is confirmed that the future pre-

Fig. 12. Results of the system in future prediction mode.

diction mode provides an accurate prediction of the burden distribution and the system contribute to supporting of burden distribution control.

4. Conclusion

By combining 3-dimensional bunker model and burden distribution model, which are based on full scale model experiment, the advanced supporting system for burden distribution control at blast furnace top with information of on-line monitoring probe data has developed.

Although the burden distribution in actual furnace operation has variations due to various factors, it was confirmed

that the system could properly analyze and grasp the burden distribution. It was also confirmed that the system could provide predictions of which tendency agrees with measured data. However, the formation process of the burden distribution is very complicated, so that the system is supposed to have inadequate points to improve. The system is now being utilized on other blast furnaces with bell-less top in our company as it continues to be improved.

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