Effect of Blast Furnace Profile on Inner Furnace States

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The effects of blast furnace profile on operation are investigated. The investigation is made by use of mathematical simulation models that are able to evaluate the operational conditions as follows: pressure drop, fuel rate and stability against channeling. The considerable number of furnace profiles are evaluated under the condition that inner volume, furnace height and hearth diameter have been given. In this investigation, geometrical parameters of furnace profile on furnace condition are clarified, and the better furnace profile for the furnace condition is shown.

KEY WORDS: blast furnace; mathematical model; furnace profile; productivity; pressure drop; fuel rate; stress in packed bed; mass and heat transfer; fluid flow.

1. Introduction

The fundamental structure of the profile of the modern blast furnace has fixed at the beginning of the twentieth century. Afterwards, the improvement in the productivity has been accomplished with the development of operation technique, such as high-temperature blast, oxygen enrichment, high pressure operation, pre-treatment of raw material, the supplement fuel injection etc., as well as progress on the facility technology, and also enlargement of furnace has proceeded. As mentioned above, the effect of the furnace profile on productivity and operation stability of the blast furnace cannot be disregarded. Basic stances on the furnace profile1–4) are as follows.

The furnace height is constrained by the strength of the coke used, because the crush of coke causes the deterioration of the permeability when the burden load exceeds the coke strength with the increase of furnace height. The “shaft” profile should be properly chosen not to prevent the smooth descent of the burden.5) And “bosh” is necessary, because the burden volume decreases by ore melting, and bosh gas must sufficiently spread to central part of the furnace, and the lower part of the furnace wall must be protected from the high-temperature gas which goes out of the raceway.

Though, as mentioned above, there are several qualitative approach for the furnace profile, quantitative guidelines which based on theoretical analysis has not be established sufficiently for the furnace profile design. Therefore, the actual profile design is made mainly by the experiential judgments based on the statistical analysis about profiles and performance data of the former or existing furnaces. This study examined the effect of the furnace profile on operational result and operation stability, by use of mathematical simulations of inner furnace states.

2. Outlines of Evaluation Process and Calculation Conditions

For the evaluation, the three mathematical simulators, that is 3-dimensional dynamic simulator for evaluating the conditions of working zone of blast furnace,6) such as material flow, temperature distribution and so on, and Mechanical stress simulator of packed bed in furnace7) were used and were interlinked to evaluate various aspects relevant to blast furnace performance.8)

In the evaluation, the blast furnace of inner furnace volume 3 000 m³ was chosen to be a target, and the furnace profile conditions were set according to Table 1. Table 2 shows the operational conditions for the evaluation. The other operational items, such as fuel rate, blast volume, etc., were obtained as results to keep the conditions. The burden distribution conditions are shown in Fig. 1. In the figure, distribution-(a) was used as a base calculation condition and (b) was used for reference to discuss the effect of bur-

Table 1. Furnace profile conditions.

| Inner volume | 3000 m³ |
|------------|--------|
| Hearth diameter | 11.7 m |
| Height (SL-tuyere) | 23.6 m |

Table 2. Operational conditions.

| Productivity (ton/m³/day) | 2.20 |
| Hot metal temperature (℃) | 1500 |
| Blast temperature (℃) | 1250 |
| Humidity (g/Nm³) | 25 |
| Top gas pressure (MPa) | 0.245 |
| O₂ addition ratio (%) | 3.0 |
| PCI rate (kg/HM) | 200. |
den distribution on the stress field. The evaluation of the stress field of packed bed in the furnace was performed under the condition of burden moving which was simulated by means of descent of bottom at periphery area instead of removing coke particles located at raceway. The physical properties of packed burden, which were used for the evaluation, are shown in Table 3.

### Table 3. Physical properties of burden.

|                 | ore  | coke |
|-----------------|------|------|
| Bulk density (kg/m³) | 1500 | 500  |
| Internal friction angle | 32°  | 32°  |
| Friction angle of wall-particle | 20°  | 20°  |

3. Results

3.1. Pressure Drop

Gas pressure patterns along the height direction at the furnace wall were compared in furnace profiles without belly in order to examine the effects of the furnace profile. The result is shown in Fig. 2 as an example. When the belly diameter to hearth diameter ratio is 1.2, the total pressure drop, which means the difference in blast pressure and top pressure, is minimum. In the larger values of the diameter ratio, the pressure drop in the lower part of the furnace decreases, though, the pressure drop in the upper part increases over it. Consequently, the total pressure is higher. On the other hand, when the diameter ratio becomes smaller than 1.2, the pressure drops both in the lower and upper part increases in comparison with those in case of 1.2 for the ratio. The increase of pressure drop in the lower part is caused by increase of gas velocity with the decrease of inner diameter, while, in the upper part, the increase of gas volume to keep productivity with the increase of fuel rate, as mentioned in the following section, increases the pressure drop against reduction effect by increasing throat diameter.

The evaluated pressure drops for all furnace profiles where the belly length is changed are plotted against the throat diameter to hearth one, as shown in Fig. 3. Total pressure drop of furnace mainly depends on shaft profile...
rather than bosh profile. The minimum value is within 0.8–0.7 of throat diameter to hearth diameter ratio. The appearance of the minimum region is brought by the same effect that is mention about Fig. 2.

These results from Figs. 2 and 3 indicate that the effect of shaft profile on pressure drop is more noticeable than bosh profile. That is to say, the pressure drop goes up through the increase of gas velocity in shaft which has small throat diameter or big belly diameter.

3.2. Fuel Rate

The fuel ratio evaluated for the furnace profile without belly was plotted against the belly diameter to hearth diameter ratio in Fig. 4, which shows that the fuel ratio decreases as the belly diameter to hearth diameter ratio increases. The result is supposed to be caused by the improvement in heat exchange and reaction efficiency through the increase in the residence time in the lower of furnace as mentioned in the previous review about furnace profile. Therefore, the fuel ratio changes low, as the bosh division is longer at the identical ratio of belly to hearth diameter.

3.3. Stress Field in Packed Bed

Figure 5 shows the vertical stress distributions of the packed bed without the existence of gas flow which were evaluated for the furnaces without belly. Features of being common in all cases are as follows.

3.3.1. General Features

In the shaft, the vertical stress at periphery is relatively smaller than the vertical stress at center, because of the effect of wall friction and the end extent shape of the furnace wall. Figure 6 shows that the magnitude of the vertical stress at center is almost equivalent to the hydrostatic pressure, and, on the other hand, that of the vertical stress at periphery is near the value estimated by Janssen’s equation.

In the bosh, the magnitude of the stress at peripheral becomes very low, because of the destressing caused by disappearance of contents in front of tuyere. On the other hand, the concentration of the stress appears at the central part region, i.e. deadman, and the magnitude of vertical stress reaches near the double of hydrostatic pressure at the tuyere level \( (P_h) \), which is estimated to be about 262 kPa by use of Eq. (1).

\[
P_h = \frac{O/C + h}{1 + \frac{O/C}{\rho_c \rho_o}} \times (H-h) + \rho_c \times h \quad \text{(1)}
\]

where \( O/C = 5.6 \) (for 287 kg/tHM of coke rate from Fig. 4), \( h = 5 \) [m], \( H = 23.6 \) [m], \( \rho_c = 600 \) [kg/m\(^3\) bed] and \( \rho_o = 1600 \) [kg/m\(^3\) bed].

And, in comparison with Fig. 7 which shows results in case of another burden distribution denoted (b) in Fig. 1, the effect of the burden distribution pattern doesn’t make any remarkable differences, so long as in the macroscopic stress pattern. Therefore, the furnace profile has a dominant effect to the stress field in the furnace.

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**Fig. 4.** Relationship between \( D_{\text{belly}}/D_{\text{hearth}} \) and fuel rate.

**Fig. 5.** Vertical stress distribution in the furnace (distribution-(a)).
3.3.2  Effects of Furnace Profile on Stress Field

Because both bosh and shaft angles decrease, when the furnace belly diameter to hearth diameter ratio increases, the vertical stress at periphery decreases in the shaft level and increases in the bosh level. On the other hand, the vertical stress which affects the deadman shows the decline by the increase of the furnace belly to hearth diameter ratio, since the ratio which supports the load of contents in bosh division increases.

The relationship between shaft angle and vertical stress value at peripheral part of shaft is shown in Fig. 8, in which the calculation results for all furnace profile both with and without belly are included. In the figure, the vertical stress level of the peripheral part tends to decrease almost linearly with the decrease of the shaft angle, i.e. the end extent shape is intensified, and, at the same time, is not receiving the direct effect of the lower furnace profile such as belly or bosh. In addition, it is noticed that around 70° of shaft angle the vertical stresses of periphery at 5 m and 10 m below stock level becomes an equal value. That is, when the shaft angle decreases to near 70°, the most of the load of packing material dissipates in furnace wall, and seldom propagates in the downward.

In this paper, the furnace profile is discussed mainly from the macroscopic viewpoint, though, when the above feature of the vertical stress at periphery is considered from the micro viewpoint such as a furnace wall profile repair in the shaft, it seems to be a certain guideline that it is made to be over 70° at the wall surface angle after the repair. In this point, Ichida et al. reported that the unusual increase of peripheral gas velocity was observed less than 71° of wall surface angle after the repair by the cold model experiment. Therefore, that suggests the close relation between channeling at periphery and magnitude of vertical stress in the shaft.

3.4. The Effect of the Furnace Profile on Channeling in Shaft

Operation stability of blast furnace can be achieved by keeping the material flows in furnace steady and regular. From the viewpoint of ensuring steady flow of solid and gas, the effect of furnace profile on the stability of furnace operation was discussed by estimating the possibility of occurrence of channeling phenomena.

Channeling phenomenon is supposed to take place when the pressure drop exceeds the vertical stress in packed bed. Sato et al. studied the mechanism of irregularity in burden decent by use of cold model experiment. According to their results, “the channeling factor” defined in Eq. (2) as the scale which measures a risk of the channeling generation is introduced, and the stability of the operation is evaluated.

\[
\text{[Channeling factor]} = \frac{\Delta P}{\sigma_V} \quad \text{(2)}
\]

Figure 9 shows an example which compares the vertical stress distribution and the gas pressure distribution which are related to channeling, in addition to the distribution of the channeling factor.

The vertical stress has the drastic distribution in the furnace, as discussed in the previous section, while gas pressure shows a radially uniform distribution, except in the lower part of the furnace. Therefore, the channeling factor becomes high at periphery, and shows the maximum value at lower shaft (a), belly (b) and in front of tuyere (c), where
stress is reduced, as shown in the figure. Figure 10 shows how the channeling factor distribution changes with the change of furnace profile. As the belly to hearth diameter ratio increases, another maximum point appears at periphery of lower shaft, in addition to in front of tuyere, and when the ratio goes up to 1.3, the region where the channeling factor exceeds 1.0 expands in the whole area of upper furnace.

Figure 11 shows the relationship between the shaft angle and the maximal value of channeling factor in upper furnace for all cases evaluated. The figure indicates a good correlation between them, though a little width caused by the effect of the other furnace parameters appears. And it indicates that it desirable requires over 80° and over 78° on the shaft angle at least in order to make the maximum channeling factor less than 1.0 under the productivity of 2.2.
4. Discussions

4.1. Throat Diameter

When Fig. 12 is compared with Fig. 3, throat diameter to hearth diameter ratio of the domestic blast furnace is approximately distributed in the pressure drop minimum range of this examination, 0.8–0.7 of throat to hearth diameter ratio. Therefore, the reasonable setting of throat diameter is supposed to be made from the viewpoint of the minimizing pressure.

4.2. Introduction of Belly to Furnace Profile

Next, the discussion is done more in detail in respect of how the stress field changes when belly (or bosh parallel) is introduced into the furnace profile. Figure 13 shows the change of the vertical stress field in introducing belly (or bosh parallel) of 3 m length into furnace body without belly at junction location between bosh and shaft. With this figure, the change has mainly appeared in the stress condition of the peripheral region, and the stress lowers in the range from the lower shaft to bosh, and in addition, the new undulation in the stress distribution of the height direction in belly division has appeared, as indicated in the arrow.

Height direction distribution pattern of the vertical stress at periphery is shown in Fig. 6. With this figure, while the stress monotonously increases from the top to the middle of shaft, in the downward, it turns to decrease, and reaches the minimum value near the lower shaft. Then, in furnace body without belly as shown in the right side of Fig. 14, after it showed the maximum value by increasing over bosh division again, it decreases tuyere zone again, and, on the other hand, in the furnace body with belly, as shown in the left side of the figure, there appears another pair of maximum and minimum points in belly zone.

So, the generation mechanism of the undulation in stress field is considered. As shown in Fig. 14, the trajectory of principal stress looks to avoid the lower end of shaft and to converge to the upper part of belly, and in addition, the similar behavior appears in the region from the lower belly to

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Fig. 12. Throat to hearth diameter ratios of domestic blast furnaces.

Fig. 13. Effect of furnace profile on stress field.

Fig. 14. Effect of belly on stress field at periphery.
bosh. Assuming that the peripheral region is in the plastic yield condition, the stress condition of this part can be expressed as Mohr’s circle shown in Fig. 15. When burden slips on the furnace wall, and yield line of wall which is defined by friction angle ($\phi_w$) intersects the Mohr’s circle at 2 points denoted A and B in the figure. The stress condition of this part must correspond to any of A or B. Point A denotes that stress condition is “active” i.e. vertical stress is larger than horizontal one, while point B denotes “passive” condition i.e. horizontal stress is larger than vertical one, because furnace wall inclination is near vertical. In the shaft region where stress condition is active, the stress condition corresponds to the point A in the figure, and moves to the point B in belly division because the stress condition changes passive by contraction flow field. Therefore, in the shaft division, the incidence angle of trajectory of principal stress for wall surface becomes ($\pi - \theta_w$)/2, and in belly division, it will changes at ($\pi - \theta_b$)/2. After all, the appearance of concentration/dispersion of trajectory of principal stress at periphery is supposed to be caused by imposition of the above constraint on the trajectory of principal stress at periphery.

Since the behavior of the stress field which appears at periphery complicatedly changes by the length and angle of each division, though the simple arguments are difficult, the comparatively clear relation between stress field and furnace shape in the shaft can be found as discussed in previous section.

4.3. Effect of Furnace Profile on Hearth

With the gas flow condition, the gas pressure drop affects it for the packing material as buoyancy. According to the basic experiment,11) this effect can be approximately taken into account by reducing the bulk density of packing material. Then, the vertical stress distribution ($\sigma^*$) on the tuyere level cross section is calculated by use of the following equations.

$$\sigma^* = \sigma \times \frac{\rho^*}{\rho} \quad \cdots \quad (3)$$

$$\rho^* = \rho - \frac{1}{g} \left( \frac{\Delta P}{\Delta L} \right) \quad \cdots \quad (4)$$

Figure 16 shows the change of vertical stress distributions for the belly to hearth diameter ratio on the furnaces without belly. The stress distributions look steep shape from deadman to raceway in front of tuyere where the stress is released by the disappearance of coke. Then, the vertical stress in deadman decreases, as the furnace profile goes pudgy, and in the belly to hearth diameter ratio of 1.4, it decreases to about 1/3 of cylindrical profile.

The relationship between vertical stress at central part of deadman and profile parameters of the bosh is shown in Fig. 17, in which the correlation can be found by classifying at the bosh length, though there is a little dispersion by the belly length. As the bosh angle decreases, the degree at which the bosh wall supports the load of the packing material increases, and, on the other hand, the vertical stress at deadman decreases. Then the effect becomes remarkable when bosh length is long.

The vertical stress at deadman is an important factor which is related to the erosion of hearth through affecting sinking level of the hearth coke. Figure 18 shows the estimated sinking level of the hearth coke to the molten pig iron by assuming hearth part packing structure as shown in Fig. 19. According to Figs.17 and 18, in case of bosh length 4 m, for example, the change of bosh angle from 78° to 74° causes the 50 kPa decrease of the vertical stress of which effect is about 1–2 m for the sinking level of hearth coke. These behaviors are supposed to affect the hearth phenome-
na such as drainage, heat load and so on.

4.4. Effect of Horizontal Stress on Operation

Above discussions about the effect of stress field in the furnace are made mainly from the viewpoint of vertical stress. As for horizontal stress, it has a larger value at the peripheral part of belly and bosh, and is supposed to have a significant effect on bridging which causes irregular descent and wearing of furnace wall. But, because any valid method for the quantitative estimation has not developed, the further discussion cannot be made and future research is expected.

5. Conclusion

The effects of blast furnace volume on efficiency of operation were evaluated from the viewpoint of reaction and heat transfer and permeability and stress field condition in the packed bed. And the effect on erosion of hearth was also estimated. The following results were obtained.

(1) There is correlation between the pressure drop and the throat diameter to hearth diameter ratio, and the minimum value exists within 0.8–0.7.

(2) It is possible to lower the fuel ratio by taking sufficient volume of the lower part of the furnace.

(3) For the shaft angle, it is desirable to be design over 80°, otherwise necessary to be over 78°.

(4) Bosh angle and bosh length affect the sinking level of the hearth coke through the applied load, and, therefore, the hearth phenomena.

Above knowledge and the mathematical simulation methods are useful and will be applied to a profile design of future blast furnaces.

Nomenclature

- \( P_h \): Hydro-static pressure (Pa)
- \( O/C \): Weight ratio of ore to coke (–)
- \( H \): Total height of bed (m)
- \( h \): Height of ore melting level from tuyere (m)
- \( \rho_c \): Bulk density of coke bed (kg/m\(^3\)-bed)
- \( \rho_o \): Bulk density of ore bed (kg/m\(^3\)-bed)
- \( \phi_c \): Friction angle between burden and wall (deg)
- \( \Delta P \): Pressure drop (Pa)
- \( L \): Distance (m)
- \( P \): Gas pressure (Pa)
- \( P_{top} \): Top gas pressure (Pa)
- \( \sigma \): Stress (Pa)
- \( \sigma^* \): Stress with gas flow (Pa)
- \( \sigma_v \): Vertical stress (i.e. Normal stress on horizontal plane) (Pa)
- \( \rho \): Bulk density of burden (kg/m\(^3\)-bed)
- \( \rho^* \): Effective bulk density including floating force by gas flow (kg/m\(^3\)-bed)

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