The Effect of the Change of Furnace Profile with the Increase in Furnace Volume on Operation

Takanobu INADA, Kouji TAKATANI, Kouzo TAKATA ¹ and Takaiku YAMAMOTO

Corporate Research & Development Laboratories, Sumitomo Metal Industries, Ltd., Hasaki-Machi, Kashima-Gun, Ibaraki-Pref. 314-0255 Japan.
¹ Steel Sheet, Plate, Titanium & Structural Steel Company, Sumitomo Metal Industries, Ltd., Hikari, Kashima-city, Ibaraki-Pref. 314-0014 Japan.

(Received on November 28, 2002; accepted in final form on March 12, 2003)

Based on the characteristics of the change of furnace profile with an increase in furnace volume, the effects of blast furnace profile on operation are investigated. The investigation is made by use of numerical simulation models that are integrated to evaluate the whole furnace state including hearth. First, the characteristics of the change of furnace profile with the increase in furnace volume are reviewed. Then, evaluation of the effects of furnace profile is made from the viewpoint of efficiency and stability of operation. The larger furnaces are advantageous to lowering a fuel rate, while stability against channeling at periphery is poor. In addition, as for furnace hearth life extension, the effect of furnace volume is discussed. As the furnace volume increases, the molten iron velocity at peripheral region of the hearth increases.

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

1. Introduction

Fundamentally, the inner volume of a blast furnace is determined in accordance with the production capacity demanded, while there exists a room for choice of the furnace volume when adjusting the number of furnaces. In Japan, blast furnaces have become larger and increased in number during the ’70s. Then, after the slow economic growth period has come, the centralization of pig production proceeded by means of replacing small furnaces with larger ones. In this trend, as well as stable operation, flexibility in productivity of each furnace has become more significant.

Among many factors that affect blast furnace phenomena and operations, the effect of the furnace profile is important. Although, from the overview of the modern blast furnaces as a chemical reactor, there are some correlations between furnace profile and its inner volume, the theoretical studies and discussions about this subject are not many and insufficient. Previous research ¹–⁵ on furnace profiles shows the following characteristics. 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. The “bosh” profile is necessary, because the burden volume decreases by ore melting, and bosh gas must sufficiently spread to the central part of the furnace, and the lower part of the furnace wall must be protected from the high-temperature gas from the raceway. There are several qualitative approaches for the furnace profile, as mentioned above, and the guidelines based on theoretical analysis have not been established, so that the furnace profiles have been designed mainly on the basis of empirical and statistical consideration.

This study was made to evaluate the effect of blast furnace profile from the viewpoint of stability and efficiency of operation, including furnace hearth erosion. In this paper, based on the blast furnace profile variation relating to the furnace volume, the effect of the blast furnace volume on operation was evaluated by means of mathematical simulation models.

2. Overview of the Change of the Blast Furnace Profile with the Increase in the Furnace Volume in Japan

Figures 1 and 2 show the typical profile parameters of blast furnaces in Japan plotted against the inner furnace volume. The tendencies in the change of the furnace profile with the increase in the furnace volume are as follows.

(1) The inner diameters increase monotonously with the increase of the furnace volume. And, the diameter ratio of throat to hearth or belly decrease, of which tendency corresponds to the dependence of shaft angle on the furnace volume.
(2) Though the heights, the distances from tuyere levels to stock levels, also increase with the increase of furnace volume, this tendency is not remarkable in furnaces of more than 2,000 m³. These above features indicate that the larger the furnaces become the dumpier the furnace shapes change. They can be represented well as numerical relationships, as shown in Table 1.
(3) The distances between tuyere levels and tap hole levels increase with the increase...
3. Outlines of Evaluation Process

For the evaluation, the following mathematical simulators were used and were interlinked to evaluate various aspects relevant to blast furnace performance, as shown in Fig. 3.

a) Three Dimensional Dynamic Simulator for Working Zone of Blast Furnace

This simulator evaluates the internal state of working zone, region from tuyere level to stock level of the furnace, by analyses of reaction, heat transfer and material flow. In addition to operational results, such as pig iron production, fuel rate and pressure drop, it outputs the internal state data, such as cohesive zone profile, gas pressure and the temperature distribution of liquid dropping down to hearth, which are used by the following simulators as boundary conditions.

b) Mechanical Stress Simulator of Packed Bed in Furnace

This simulator based on the elastic–plastic theory evaluates the stress field of moving packed-bed in furnace. The evaluated stress field of the inner furnace is used for the estimation of the possibility of channeling, and as input data for the following simulator, the coke profile sunk into hot metal bath is evaluated by use of the vertical stress data at the bottom surface of the bed, which this simulator outputs.

c) Simulator of Molten Iron Flow and Heat-transfer in Hearth

This simulator evaluates the molten iron velocity field and temperature profile of furnace hearth including refractory region, by analyses of heat transfer and momentum.
transfer. In the calculation, the thermo-chemical solution process of hearth refractory is also taken into account by removing pieces of brick in the erosion condition, so that the thermal-equilibrium surface profile of hearth refractory, as well as erosion process, can be evaluated.

4. Calculation Conditions

The furnace profile conditions were set according to Table 1 as mentioned in Chap. 2. Table 2 shows the operational conditions for the evaluation. The other operational items, such as fuel rate and blast volume, were obtained as results to keep the conditions. For setting burden distribution condition for each furnace volume shown in Fig. 4, the burden distribution mathematical model was used. The calculation was made under the geometrical conditions that vertical dimensions of charging apparatus were constant and the square root of horizontal dimensions were linear functions of the furnace volume.

The stress field of packed bed in the furnace was evaluated under the condition of burden moving which was caused by the descent of the bottom at the periphery area corresponding to raceway. The physical properties of packed burden used for the evaluation are shown in Table 3.

5. Results

5.1. Temperature Distribution

As shown in Fig. 5, any remarkable differences are not found among furnaces of various volumes, so that the furnace volume itself doesn’t affect the macroscopic heat pattern of the furnace so long as the similarity of burden distribution conditions is kept.

5.2. Pressure Drop

Despite the productivity remaining constant, the pressure drops of gas increase with the increase of furnace volume, as shown in Fig. 6. Figure 7 shows the vertical distributions of pressure drops at periphery. In this figure, the difference in the total pressure drops of the furnaces of various volumes appears to originate from the difference in the pressure drops in the shaft region. Figure 7 shows that the top gas velocities also increase with the increase of furnace volume. On the other hand, blast rate decreases with the increase of furnace volume because fuel rate decreases with the increase of furnace volume, as mentioned in the following section. Therefore, the feature of furnace profile variation, as mentioned in the previous section, that the throat diameter to hearth diameter ratio of larger furnaces is smaller than that of smaller furnaces is supposed to cause increases in the gas velocities and to increase the pressure drops at larger furnaces. It should be noted that the top pressure of the large blast furnace actually tends to be higher than that of the small blast furnace. The tendency is effective in reducing the increases in the gas velocities of larger furnaces.

Table 2. Operational conditions.

| Productivity (ton/m³/day) | 2.20 |
|--------------------------|------|
| Pig temperature (°C)     | 1496 |
| Blast temperature (°C)   | 1250 |
| Humidity (g/Nm³)         | 25   |
| Top gas pressure (MPa)   | 0.245|
| O₂ addition ratio (%)    | 3.0  |
| PCI rate (kg/HM)         | 210  |

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°  |
5.3. Fuel Rate

As shown in Fig. 8, the heat loss ratio decreases with the increase of furnace volume, because the surface area to volume ratio of larger furnace is lower than that of smaller one. Therefore, larger furnaces are more efficient in heat utilization. However, the effect on the improvement of the fuel rate is no more than 3 kg/tHM, as there is no noticeable difference in temperature profiles among furnaces of various volumes, as shown in Fig. 5.

5.4. Stress Field of Packed Bed in the Furnace

Figure 9 shows the vertical stress distributions in the furnaces of various volumes, which are evaluated without gas flow effects. Common features in all cases are as follows.

In the shaft region, while the vertical stress applied at the center is almost as much as hydrostatic pressure, the vertical stress is relatively low at periphery because of the friction with wall and the shape that spreads downward. On the other hand, in the lower region of the furnace, the concentration of stress appears at center of deadman, where the stress reaches the double of the hydrostatic pressure, while the stress is released around the raceway as the disappearance point of coke.

As for features of change in vertical stress filed with increase of inner volume, the vertical stress at periphery of large furnace is lower than small furnace, meanwhile at center of deadman vertical stress of large furnace is higher than that of small furnace. The cause of the former feature
is because the shaft angle decreases as the furnace becomes large. Figure 10 shows Mohr’s circle that expresses the stress state at the wall. The wall yield line crosses with the Mohr’s circle, because burden slips on the wall surface. In the figure, the stress state at the wall surface is correspondent with point A, because vertical stress surpasses horizontal stress in the shaft region. Therefore, the vertical stress, i.e. normal stress applied on horizontal surface, is indicated as $\sigma$-coordinate ($\sigma_v$) of point P, and it lowers, while the shaft angle ($\theta$) decreases. The cause of the latter feature is that drag and frictional force from the wall surface do not sufficiently reach to the furnace central part, since the throat diameter of large furnace is big, and the height is tall.

6. Discussions

6.1. Effect on Stability of Operation

Stability of blast furnace operation can be identified with regularity of material flow in the furnace. Sato et al. studied the mechanism of irregularity in burden decent by use of cold model experiment. According to their results, as an index for measuring the possibility of abnormality in gas and solid flow, a variable named channeling factor defined in Eq. (1) was introduced. From the definition below the abnormality is theoretically supposed to occur where this scale is more than unity.

$$\text{Channeling factor} = \frac{P - P_{\text{top}}}{\sigma_v} \quad \ldots \ldots \ldots (1)$$

The channeling factor distributions in the furnaces of various volumes are shown in Fig. 11. By comparison among the contour lines in the figure, the area of more than 0.5, for example, can be found extensively in the peripheral region of the large blast furnaces. This feature is led by the decrease of shaft angle with the increase of furnace volume, which causes release of vertical stress, and the increase of pressure drop. Therefore, the profiles of the large blast furnaces are supposed to be disadvantageous for prevention of channeling. The different region where channeling factor exceeds unity exists in front of the tuyere. This region is supposed to correspond to raceway formation, though, the quantitatively evaluation of raceway shape is difficult because the simulations were based on continuum media.

6.2. Effect on Hearth Erosion

According to previous reports on dissection investigation of blast furnaces, hearths are not fully packed with coke. As the previous work emphasized, it is important for the appropriate estimation of molten iron flow and thermo-chemical erosion to take the filling condition of the furnace hearth into account. Therefore, by using the stress analysis results, the occupation conditions of coke in hearths were estimated in this work.

6.2.1. Estimation of Coke Profile in Hearth

Since the hearth coke sinks in the molten pig iron due to the load of burden in addition to its own weight, the coke occupied region in hearth can be estimated based on of the balance of forces, as follows. Firstly, the load of burden, which affects the hearth coke can be obtained as vertical stress at tuyere level. Secondly, the effect of gas flow was
taken into account by considering that floating force by gas flow decreases the apparent density of the burden, as shown in Eqs. (2) and (3).

\[
\sigma^* = \sigma \times \frac{\rho^*}{\rho} \quad \text{...............(2)}
\]

\[
\rho^* = \rho \times \left(\frac{\Delta P}{\Delta L}\right) \quad \text{...............(3)}
\]

Lastly, by assuming the packing condition shown in Fig. 12, the sinking level of the coke in the hearth at each radial position can be evaluated from a balance between the load received from the packing material of the upper part from the tuyere and the buoyancy received from the molten pig iron. As shown in Fig. 13, the coke profile is steep, however, the slope angle of the coke bed surface is supposed not to exceed a certain intrinsic angle, such as the repose angle of the charged burden at the top of the furnace. Therefore, the slope angle was assumed to be equal to the internal friction angle, which was measured by tri-axial test as shown in the figure. While the sinking levels of coke at the center become deeper with the increase of furnace volume, the coke free space exists at the bottom corner region in the initial stage for either case of furnace volume.

6.2.2. Estimation of Thermal Equilibrium Erosion of the Hearth

Besides hearth dimension, the erosion of the hearth is influenced by the refractory layout. Therefore, the estimation was made on the assumption of the hearth refractory layout as shown in Fig. 14. As for the dimension of the hearth
with respect to furnace volume, the hearth diameters were
determined according to the correlation equation listed in
Table 1. On the other hand, the depth of the hearth and the
radial thickness of refractory at the sidewall were fixed.
Table 4 shows the properties of refractory, including the
erosion criteria for the simulation.

The results are shown in Fig. 15. While the thermal equi-
librium erosion profile of every furnace volume looks like
"the pot base type", the residual thickness of refractory at
the sidewall and bottom decreases with the increase of fur-
nace volume and with the increase of productivity, as
shown in Fig. 16. The thermo-chemical solution of hearth
refractory is caused by exposure to the high-temperature
molten pig iron, and the temperature of molten pig iron is
related to its own flow rate. According to the above consid-
eration, the following effects that brought about the results
above can be pointed out.

Since the increase in the furnace volume is mainly done
by the extension of the furnace cross section, the pig iron
production per unit of cross section is almost independent
of the furnace volume. Then, since tap holes are located in
the hearth wall and the coke free space exists at the bottom
corner part, the molten pig iron tends to flow in the periph-
eral part region, of which volume is supposed to be propor-
tional to circumference of the furnace hearth. Therefore, in
the identical productivity base, the velocity of molten pig
iron in the peripheral part region is proportional to the fur-
nace volume, as shown in Fig. 17. So, the appropriate
choice and layout of the hearth refractory, as well as lower-
ing heat load operation, are important for larger blast fur-
naces to ensure sufficient thickness of residual refractory.

On the other hand, the dependence of bottom erosion on
furnace volume can be considered as following. When
molten pig iron is tapped from tap hole in the right side, as
shown Fig. 16, the molten iron velocity at the hearth bottom
can be considered simply as the mean velocity of molten
pig iron that passes through longitudinal section including
central axis from the left to the right. So, molten iron veloc-
ity at the hearth bottom increases with the increase of fur-
nace volume, when initial depth of the hearth bottom is
fixed. Therefore, it is preferable to increase the initial depth
of the hearth according to furnace volume, and the tenden-
cy like this can be found in actual hearth design, as shown
in Fig. 2.

7. Conclusion

Based on characteristics of profile variation in accord-
ance with furnace volume, the effects of blast furnace vol-
ume on efficiency of operation were evaluated from the
viewpoint of reaction, heat transfer, permeability and stress
field condition in the packed bed. And the effect on erosion
of the hearth was also estimated. The following results were
The pressure drop shows the tendency to increase with extension with respect to the inner furnace volume, which is caused by the decrease of the throat to hearth diameter ratio.

As for thermal efficiency, though, heat loss ratio decreases as the furnace volume increases, which can be said to be advantageous for large blast furnaces, and the effect is not noticeable in the fuel rate.

Because a risk of channeling at periphery is high for larger blast furnaces of which shaft angles are smaller, the upper limit of productivity is constrained.

The erosion of hearth refractory increases on the large blast furnace in comparison with small blast furnace. Therefore, it is supposed that the erosion control of the hearth requires the consideration to refractory layout and to operation for lowering heat load.

The mathematical simulators used in this work are also useful for profile designs of future blast furnaces.

**Nomenclature**

- $\Delta P$ : 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)

**REFERENCES**

1) M. A. Pavlov: Metallurgy of Pig Iron, vol. 3, Verlag Technik, Berlin, (1953), 95.
2) H-K Wapler and C. Wagner: Stahl Eisen, 95 (1975), 1079
3) A. Shigemi: Seisen Handbook, Chijin Shokan, Tokyo, (1979), 252.
4) A. K. Biswas: Principles of Blast Furnace Ironmaking, Cootha Publishing House, Brisbane, Australia, (1981), 483.
5) M. Shimizu, A. Yamaguchi, S. Inaba and K. Narita: Tetsu-to-Hagané, 68 (1982), 936.
6) K. Takatani, T. Inada and Y. Ujisawa: ISIJ Int., 39 (1999), 15.
7) K. Katayama, S. Wakabayashi, T. Inada, K. Takatani and H. Yamanka: Tetsu-to-Hagané, 83 (1997), 91.
8) K. Takatani, T. Inada and K. Takata: ISIJ Int., 41 (2001), 1139.
9) T. Sato, K. Takeda and H. Itaya: CAMP-ISIJ, 9 (1996), 750.
10) K. Kanbara, T. Hagiwara, A. Shigemi, S. Kondo, Y. Kanayama, K. Wakabayashi and N. Hiramoto: Tetsu-to-Hagané, 62 (1976), 355.
11) S. Hashizume, H. Takahashi, T. Nakagawa, S. Tomita, M. Sato, Y. Morioka and T. Kostabashi: Tetsu-to-Hagané, 64 (1978), S108.
12) M. Tachimori, J. Ohno, M. Nakamura and Y. Hara: Tetsu-to-Hagané, 70 (1984), 2224.
13) Y. Tomita, H. Ogasu and T. Fukuda: Nisshin Seiko Gihou, 56 (1987), 1.
14) K. Shibata, Y. Kimura, M. Shimizu and S. Inaba: CAMP-ISIJ, 1 (1988), 1073.