Development of the Burden Distribution and Gas Flow Model in the Blast Furnace Shaft

Jong-In PARK,1) Ui-Hyun BAEK,1) Kyoung-Soo JANG,1) Han-Sang OH2) and Jeong-Whan HAN1)

1) School of Materials Science and Engineering, Inha University, Incheon, 402-751 Korea. E-mail: jjongins2@paran.com, backchahyun@naver.com, smile__ks@hotmail.com, jwhan@inha.ac.kr
2) Technical Research Center, Hyundai Steel, Dangjin-Gun, Chungnam, 167-32 Korea. E-mail: 0hs51s@hyundai-steel.com

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It is important to control the burden distribution, which affects the gas flow pattern in the blast furnace. Therefore, a burden distribution analysis model is needed to predict the burden profile. In this study, the burden descent and gas flow models were developed to complete a blast furnace analysis model. A previous study reported two models based on the burden trajectory and stock model. The burden profile that is due to the burden trajectory was calculated using stock model in the upper part of shaft. The entire burden profile, which is classified into five burden types calculated using the descent model, was used for a gas flow calculation as the initial conditions in the gas flow model. The analysis models were developed using a visual basic based spread sheet, and compared with the 1/12 scaled model experiment. In addition, a GUI (Graphic User Interface) was added for the convenience of the operators.

KEY WORDS: burden distribution; numerical analysis; modeling; burden descent.

1. Introduction

In the blast furnace (BF), the gas flow pattern is dominated by the mean thickness of the coke and ore layers, since the permeability and surface area according to the burden type are different and affect the gas pressure loss.2) Therefore, it is essential to predict and control the burden distribution for an efficiency improvement of iron-making. On the other hand, it is very difficult to measure internal flows directly and understand the phenomena inside the blast furnace (BF) because of the high temperature and hazardous conditions. In addition, considerable effort and time is needed to disassemble a BF. Therefore, simulation models are useful for predicting the phenomena inside a BF. Thus far, 1-dimensional2,3) based on the kinetics and 1-dimensional dynamic model,4) 2-dimensional steady state model,5) three-dimensional steady-state simulation model,6) and non-steady state model were developed to examine the inner state of a BF. In previous studies, the burden materials are mostly assumed to be a mixed layer of ore and coke. Therefore, it is difficult to examine the gas flow affected by the burden distribution.

A recent study7) developed a burden trajectory and stock model, and calculated the burden profile at the upper part of the shaft. To complete the analysis model for the burden distribution, the descent model was added. The shape of the burden layer stacked on the upper part changes when the burden descends, because the descending velocity affected by the operating variables is different along the radial direction. In this study, the descending velocity was calculated using the 1/12 scaled model, and it was applied to the analysis model. The burden profiles calculated from the burden trajectory and stock model were used as initial conditions in the descent model. As a result, the program involving an analysis model for the fall, stack and descent of the burden simulated the behavior of the burden using several algorithms. Consequently, the overall burden profile was calculated, and used for the gas flow model. After the burden profile calculation, layers including five burden types were divided into cells with information on the properties. For a gas flow calculation, the pressure drop was calculated using Ergun’s Eq.13) in each cell.

In this study, visual basic based spread sheet was used to develop the burden distribution and gas flow model. This is a widely applied spread sheet that includes numerical analysis for the iron-making process. This analysis model that runs in a spread sheet includes a GUI (Graphic User Interface) developed via visual basic coding. The GUI menu is divided approximately into three parts, calculation conditions, program run and results. The operators can easily set up the boundary conditions, such as the notch angle, charging pattern, shape of a blast furnace and burden properties, in the calculation condition sections. The results section displays the Lc/Lc graph, burden profile, gas flow distribution, etc. On the other hand, chemical reactions, such as the reduction of iron oxides, the boudouard reaction are yet to be considered.

2. Numerical Method

It is important to understand the burden distribution in advance of a calculation of the gas flow distribution. For this purpose, the burden trajectory and profile were calculated using the falling and stock model in a previous study.12) The
results of the previous model were applied to the stock model, and the gas flow distribution was calculated. Figure 1 shows the concept of this analysis model. Four models are linked and successive calculations are possible.

2.1. Descent Model

The burden will descend to the lower part by the discharge of pig iron and slag. Therefore, all particles have a moving velocity to the lower part. The descending velocity distribution along the radial direction is determined by multiple factors, such as the shape change of the furnace, inter-particle and particle-to-wall collisions, inner stress and phase transition. To calculate the complete profile of the burden, it is important to determine the velocity distribution along the radial direction and the change in layer shape.

There are some assumptions for the calculations in this model. Firstly, the BF process is presumed to be a pack bed of solid particles. In addition, the shape of the dead man zone was fixed, and it is assumed that there was no movement of burden toward the dead man zone. The burden descent is considered to be the movement of the stock line composed of approximately a hundred dots in radius because it is impossible to calculate all the descending particles in a real scale.

To calculate the movement of the stock line, the stock line in the upper part resulted by the stock model was used as the initial condition of the burden surface. In a previous study, the burden trajectory and batch burden profile could be calculated using the stock model.12) Figure 2 shows the results of the stock model. There were two main stock lines at the top and bottom of a batch stock layer and four additional stock lines for separating the burden types.

In Fig. 3, the top layer SL1 calculated by the stock model moves to the lower part by the batch volume, and becomes SL2. The movement of the stock line can be explained by the movement of dots. One of the dots, \((x_1, y_1)\) on the SL1 moves to \((x_2, y_2)\) by vertical and horizontal distances. The vertical moving distance from SL1 to SL2, \(\Delta y\) is initially the mean data of the experimental result by a batch volume, and was then modified by the descending velocity along the radial direction. The velocity distribution along the radial direction affects each \(\Delta y\). The dots cannot descend only vertically because the blast furnace diameter becomes wider by passing the furnace shaft. Therefore, the interval among dots will increase regularly as the blast furnace diameter is increased.

After the vertical and horizontal movement of dots, the area of \(a_i\) in Fig. 3 will be summed and compared with the real charging volume by converting to volume. To calculate the area of \(a_i\), the area between SL1 and SL2 was divided into several quadrangles composed of four dots, and a quadrangle was divided into two triangles in Fig. 4. The area between SL1 and SL2 was calculated using the sum of \(a_i\). The area of \(a_i\) can be calculated by Eq. (1).

\[
a_i = \frac{1}{2} |x_1y_2 + x_2y_3 + x_3y_4 + x_4y_1 - y_1x_2 - y_2x_3 - y_3x_4 - y_4x_1| \tag{1}
\]

In Fig. 5, \(a_i\) was converted to volume \(V_i\) by axially rotation. The volume of a ring, \(V_i\), and the total volume surrounded by SL1 and SL2, \(V_{\text{total}}\) were calculated using Eqs. (2) and (3).

\[
V_i = a_i \cdot 2 \cdot \pi \cdot r_i \tag{2}
\]

\[
V_{\text{total}} = \sum_{i=1}^{n} V_i \tag{3}
\]
Since $V_{\text{total}}$ is changed by the vertical moving distance, SL2 will be moved vertically until an iteration criterion, which is a gap between $V_{\text{total}}$ and the real charging volume is satisfied within a tolerance. The height of the layer can be decided, and the stock line will be formed. After the calculations, another stock line will be formed continuously at the lower part in the same method.

When the burden descends, additional stock lines for separating the burden types should also descend. Figure 6 shows a schematic diagram of the moving method of additional stock lines. Since additional stock lines are composed of dots, the movement of lines can be explained by the movement of dots. The individual dots on additional lines calculated by the stock model have location information. In the upper layer, $h/H$ and $r/R$ are determined as initial location information. To calculate the additional stock lines, $h/H=h_1/H_1$ and $r/R=r_1/R_1$ were assumed in all batch layers.

The entire burden profile was compared according to the charging pattern to confirm the change in profile calculated using the analysis model. Tables 1, 2 and 3 list the charging notch, burden properties and charging pattern, respectively.

### 2.2. Gas Flow Model

In this study, the gas flow distribution was calculated by assuming that all materials were solid. The permeability and friction of particles affect the gas flow pattern while passing through a pack bed. Most studies on the iron-making modeling assume that all particles have a homogeneous composition or an ore and a coke layer combine to a unit layer. On the other hand, the layers were divided into five parts in this study; ore large, ore small, coke base, center coke and mixed layer. Therefore, it is possible to calculate the more accurate gas velocity distribution.

Each section according to the burden types was separated into cells with information, such as diameter, porosity and shape factor in Fig. 7(a). The variables can be used for Ergun’s equation that calculates the pressure drop of injected gas. Figure 7(b) shows the transformation from stock line to the gas flow distribution.

Figure 8 shows the process for calculating the gas velocity. Firstly, $\Delta P_1$ that is the gap between the pressure at the tuyere and burden surface was determined by the initial condition. $\Delta P_1$ was used to calculate $V_1$, the initial gas velocity distribution. For a more accurate calculation, $\Delta P_2$ was calculated using Ergun’s equation including $V_1$ as a velocity term as follows:

$$\Delta P = \frac{150(1-\varepsilon)^2 v_g^2}{\varepsilon \Phi (D_p)^2} + \frac{1.75(1-\varepsilon)^2 v_g^2 \rho \rho_L}{\varepsilon \Phi (D_p)^2} \ldots .. (4)$$

where, $\varepsilon$, $v_g$, $\Phi$, $D_p$, $\rho$ represents porosity, gas velocity, shape factor, particle diameter and gas density.

Subsequently, pressure distribution excluded the permeability of the burden was calculated using the FDM (finite difference method). The measurement data of a BF was applied to the pressure boundary condition at the inner wall.

### Table 1. The charging notch of a chute.

| Notch | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|-------|---|---|---|---|---|---|---|---|---|----|----|
| Angle (deg.) | 47 | 45 | 43 | 41 | 38 | 36 | 33 | 30 | 26 | 23 | 3  |

### Table 2. The burden properties used for the analysis model.

| Diameter (m) | Density (Kg/m$^3$) | Shape factor | Coef. of friction |
|--------------|---------------------|--------------|------------------|
| O$_L$        | 0.03                | 2500         | 0.77             | 1                |
| O$_S$        | 0.01                | 2500         | 0.61             | 1                |
| C$_B$        | 0.05                | 550          | 0.81             | 1.1              |
| C$_C$        | 0.07                | 550          | 0.89             | 1.1              |

### Table 3. The charging pattern used for the analysis model.

| Mode | Batch weight (ton) |
|------|-------------------|
| O/C  |                   |

| Case 1 | Notch  | O$_L$ | C | O$_S$ | O$_C$ | O$_L$ | O$_S$ | O$_C$ | O/C  |
|--------|--------|-------|---|-------|-------|-------|-------|-------|------|
| Revolution | 4 5 6 7 8 | 2 3 4 5 6 | 11 | 1 2 3 | 100 30 25 4 | 4.61 |
| Case 2 | Notch  | O$_L$ | O$_S$ | O$_C$ | O$_L$ | O$_S$ | O$_C$ | O/C  |
| Revolution | 2 3 4 5 6 | 4 5 6 7 8 | 11 | 1 2 3 | 100 30 25 4 | 4.61 |
| Case 3 | Notch  | O$_L$ | O$_S$ | O$_C$ | O$_L$ | O$_S$ | O$_C$ | O/C  |
| Revolution | 2 3 4 5 6 | 4 5 6 7 8 | 11 | 1 2 3 | 90 27 35 7 | 2.83 |
surface as an initial condition. The calculation procedure of the FDM is described below.

\[
\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} = 0 \quad \text{........................... (5)}
\]

where, \( \psi \) is the steam function.

\[
u = \frac{\partial \psi}{\partial y}, \quad \nu = \frac{\partial \psi}{\partial x} \quad \text{........................... (6)}
\]

\[
\frac{\partial^2 \psi}{\partial x^2} = \frac{\psi_{i+1,j} - 2\psi_{i,j} + \psi_{i-1,j}}{\Delta x^2} \quad \text{........................... (7)}
\]

\[
\frac{\partial^2 \psi}{\partial y^2} = \frac{\psi_{i,j+1} - 2\psi_{i,j} + \psi_{i,j-1}}{\Delta y^2} \quad \text{........................... (8)}
\]

\[
\frac{1}{\Delta x^2} = \left( \frac{\psi_{i+1,j} - 2\psi_{i,j} + \psi_{i-1,j}}{\Delta y^2} \right) = 0 \quad \text{........................... (9)}
\]

After the \( P_1 \) is determined by an iterative calculation due to FDM, \( P_1 \) is multiplied by \( \Delta P_2 \) considering the air resistance according to the burden type to obtain \( \Delta P_3 \), final pressure distribution. \( \Delta P_3 \) will replace the pressure drop term of Ergun’s equation to obtain a quadratic equation that includes the gas velocity terms as a root. The final gas velocity distribution, \( V_2 \) was calculated by solving a quadratic equation.

Since the gas flow is calculated in each cell, it is important to know the burden properties according to the position of each cell. The friction coefficient of the burden is differentiated by the particle size, and is related to the moving distance on the slope. Therefore, it will differentiate the radial particle size distribution of the burden depending on the type of material. In addition, the particle size distribution affects the shape factor and porosity distribution. Figure 9 shows the relative particle sizes of ore and coke with respect to the radial direction. The radial distribution of the particle size was considered using the data in Fig. 9.\(^{14}\)

Equations (10) and (11) were used to consider the distribution of the shape factor due to the particle size.\(^{15}\)

\[
\Phi_{\text{coke}} = 0.390 \log(D_p) + 1.331 \quad \text{........................... (10)}
\]

\[
\Phi_{\text{Ore}} = 0.328 \log(D_p) + 1.268 \quad \text{........................... (11)}
\]

\( \Phi_{\text{coke}} \) and \( \Phi_{\text{Ore}} \) are the shape factor of coke and iron ore, and \( D_p \) is the particle diameter. In addition, the porosity distribution due to the particle size distribution was considered. The porosity of coke and iron ore can be obtained using Eqs. (12) to (19).\(^{16}\)

\[
\varepsilon_C = (0.153 \log D_p + 0.418)(1 - \Delta \varepsilon) \quad \text{........................... (12)}
\]

\[
\Delta \varepsilon = 1.225 \times 10^{-2} \times I_s^{0.416} \quad \text{........................... (13)}
\]

\[
\varepsilon_O = (0.403 \log D_p - 0.14)(1 - \Delta \varepsilon) \quad \text{........................... (14)}
\]

\[
\Delta \varepsilon = 1.64 \times 10^{-3} \times I_p^{1.006} \quad \text{........................... (15)}
\]

\( \varepsilon_C \) and \( \varepsilon_O \) are the porosities of the coke and iron ore, respectively, and are affected by the particle size, \( I_s \), and \( I_p \). \( I_s \) and \( I_p \) are defined by the following:

\[
I_s = D_p^2 \sum wi(1/di - 1/D_p)^2 \quad \text{........................... (16)}
\]

\[
I_p = (1/D_p)^2 \sum wi(di - D_p)^2 \quad \text{........................... (17)}
\]

\[
I_{sp} = 100(I_s \cdot I_p)^{0.5} \quad \text{........................... (18)}
\]

\[
D_p = 1/\sum (wi \cdot di) \quad \text{........................... (19)}
\]

\( wi \) is the weight percent per particle size, and \( di \) is the representative particle diameter.

3. Experimental Method

The burden profile of the analysis model was compared with a 1/12 scaled model in the same charging pattern to check its validity. Table 4 lists the burden property accord-
ing to burden type, and the notch angle and charging pattern are listed in Tables 1 and 5. The burden was charged by the order of the coke base (CB), ore large (OL), ore small (OS), and center coke (CC). In the apparatus, the burden discharge and descent were represented by the descent of the lift. Initially, the burden is stacked on the fixed lift located in the approximately half height, while the burden level increases to the top of the shaft part. The lift descends to keep the level of stock line because of the continuous charging of the burden until the lift reaches the lower part of an apparatus.

The measurement of the descending velocity in the radial direction was conducted in the 1/12 scaled model for applications to the analysis model. A total of nineteen tracers were placed between the ore and coke layer in 5 cm intervals, and the position of the tracer was measured every five minutes. The mean descending velocity of a lift was set up as 2.5 cm/min. Figure 10 shows the tracers in a 1/12 scaled model apparatus.

In Fig. 11, the descending velocity tends to increase when moving from the center to the wall because the blast furnace diameter increases when the burden descends in a shaft part. Many factors affect the descending velocity, such as the friction force between particles and the walls, shape of the dead man zone, etc. On the other hand, it is difficult to consider all variables. Therefore, the scaled model experimental data of this case was used for the analysis model.

Figure 12 shows the burden profile of the experimental result compared to the analysis model result after descent. Coke was colored in white to differentiate with iron ore. Overall, both results have a similar profile except for the shape of the center coke layer because a dead man zone does not exist in the scaled model. In Fig. 12(c), the stock line is expressed in detail. There are ore large, ore small, coke base and center coke with a mixed layer, which is exists between the ore large and coke layer.

4. Results and Discussion

4.1. Burden Distribution

The whole burden profiles were calculated using the present model according to the charging pattern and the change in the weight percent of the burden. Three cases were analyzed to compare the burden profiles. The charging pattern in CASE 1 and the weight percent of the burden in

| Diameter (m) | Density (Kg/m³) | Shape factor |
|--------------|-----------------|--------------|
| OL           | 0.006           | 2500         | 0.77         |
| OS           | 0.003           | 2500         | 0.61         |
| CB           | 0.007           | 550          | 0.81         |
| CC           | 0.010           | 550          | 0.89         |

Table 4. The burden properties used for the scaled model experiment.

| Mode   | Batch weight (ton) | O/C |
|--------|--------------------|-----|
| Notch  | CB  2  O  3  Cb  4  Os  5  Cc  6  C  7  Cc  8  | CB 1  Os 1  Cc 2  Os 3  |
| Revolution | CB  2  O  2  Cb  2  Os  2  Cc  2  C  2  Cc  2  | CB 1  Os 1  Cc 2  Os 3  |

Table 5. The charging pattern used for the scaled model.
CASE 3 were changed from standard CASE 2. Figure 13 shows the burden profiles of the three cases. Tables 1 and 3 list the charging notch and pattern for an analysis of the burden distribution.

In CASE 1, the notch number of the coke base and ore large were larger and smaller than CASE 2, respectively. The coke layer moved to the center when compared with CASE 2, since the falling distance of coke from the center was shorter than in CASE 2. In addition, the thickness of the ore large layer became thicker in the side part because of the change in the charging pattern, and it increases the reposed angle of ore large in CASE 1. For this reason, ore small slides down, and is widely spread on the ore large layer in CASE 1 compared to CASE 2. In CASE 1, the change in charging pattern will cause gas flow toward the center part.

In a comparison of CASE 2 and CASE 3, the thickness of the stock layer increased because the weight percent of coke, which have a low density, increased in CASE 3. In Fig. 13, the thickness of coke layer and coke base of CASE 3 were larger than CASE 2, but the shape of the stock layer was similar to CASE 2. Owing to the growth of the coke layer thickness, it can be expected that the injected gas will go through the shaft part easily.

In Fig. 14, the graphs show LO/LC at the upper part of the shaft and belly part. Three cases have different LO/LC patterns. In CASE 2, LO/LC was < 3 and high in the middle of the radius. On the other hand, the LO/Lc of CASE 1 increased along the radius direction. In CASE 3, LO/Lc is relatively reduced due to the increase in the weight percent of coke. The depth ratios at the upper part of the shaft and belly part were similar, but the depth ratio in center part was relatively unstable because of a deadman zone.

4.2. Gas Flow Distribution

The burden profiles were calculated using the descent model, and used to calculate the gas velocity. Figure 15 shows the gas velocity distribution of each case calculated using a gas flow model. The gas velocity distribution was differentiated in each layer because the permeability according to burden type was different. The gas velocity tends to increase toward the center and upper part of a BF.

To compare the gas velocity along the radial and height direction of a BF, the diameter of a BF is divided into four parts in Fig. 16. Figure 17 shows the gas velocity distribution along the height of the blast furnace in the center, middle and wall parts. The gas velocity decreases at side part of a BF due to the effect of an ore large and ore small, which have a low permeability in the graphs. In the center part, all cases showed similar gas velocities. In the other parts, the gas velocity of CASE 3, which has a low LO/Lc, increased.
In CASE 1 in Fig. 13, the ore small layers are distributed widely on the ore large layers because the particles of ore small slide down due to the reposed angle of ore large. This disturbs the gas flow, and the gas velocity of CASE 1 decreases in the middle part. To solve this problem, it is necessary that a terrace be formed at the wall part. In addition, the gap between CASE 1 and CASE 2 increases in the wall part compared to the middle part, because \( \text{LO}/\text{LC} \) increases along the radial direction.

5. Conclusions

The analysis model for the burden distribution and gas flow was developed by mathematical modeling and compared with the 1/12 scaled model experiment. Visual basic based spread sheet was used to calculate the entire burden profile and gas flow patterns.

The descending velocity along the radial direction resulting from the 1/12 scaled model experiment was used for the descent model. In addition, the stock model results were used as the initial condition for the gas flow model. The burden materials in the blast furnace were classified into ore large, ore small, coke base and center coke including an additional mixed layer. In the case study, the burden profiles were varied by altering the charging pattern and operating conditions, and \( \text{LO}/\text{LC} \) affected the gas flow distribution.

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REFERENCES

1) T. L. Joseph: Trans. AIME, 167 (1946), 15.
2) I. Muchi: Trans. Iron Steel Inst. Jpn., 7 (1967), 223.
3) J. Yagi and I. Muchi: Trans. Iron Steel Inst. Jpn., 10 (1970), 392.
4) M. Hatano, K. Kurita and H. Yamaoka: Tetsu-to-Hagané, 68 (1982), 2369.
5) R. Wartman: Stahl Eisen, 95 (1975), 442.
6) H. Kubo, T. Nishiyama and S. Taguchi: Kawasaki Steel Giho, 14 (1982), 134.
7) J. Yagi, K. Takeda and Y. Omori: Tetsu-to-Hagané, 66 (1980), 1888.
8) M. Hatano and K. Kurita: Tetsu-to-Hagané, 66 (1980), 1898.
9) M. Kuwabara, S. Takane, K. Sekito and I. Muchi: Tetsu-to-Hagané, 77 (1991), 1593.
10) T. Sugiyaama and M. Sugata: Seitetsukagaku, 325 (1987), 34.
11) J. A. Castro, H. Nogami and J. Yagi: ISIJ Int., 39 (1999), 15.
12) J. I. Park, H. J. Jung, M. K. Jo, H. S. Oh and J. W. Han: Met. Mater. Int., 17 (2011), paper accepted.
13) S. Ergun: Chem. Engr. Progress, 48 (1952), 227.
14) S. K. Jung, C. Y. Beak and W. S. Chung: J. Kor. Inst. Met. & Mater., 39 (2001).
15) M. Ichida, Y. Isozaki and K. Tamura: Tetsu-to-Hagané, 77 (1991), 1561.
16) G. H. Geiger and D. R. Poirier: Transport Phenomena in Metallurgy, Addison-Wesley, Boston, (1973), 91.