Numerical Investigation on Effects of Deadman Structure and Powder Properties on Gas and Powder Flows in Lower Part of Blast Furnace

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Deposition of excessive amount of fine powder in the lower part of blast furnace deteriorates permeability of packed bed for reacting gas and liquid products, and causes operation instability. Powder behavior in the lower part of blast furnace has been attracting technical and scientific interests with increase in injection rate of pulverized coal into blast furnace. This study performed numerical experiments on effects of deadman structure and properties of generated powder on gas and powder flow behavior in the lower part of blast furnace by using two-dimensional axisymmetric mathematical model for flow and heat transfer in blast furnace based on multi-fluid theory. Among the packed bed properties, voidage has greater effect than coke diameter on penetration of high temperature gas and powder into the deadman zone and pressure drop in the furnace. The deadman having extremely low voidage is possibly to cause formation of low temperature zone in the deadman. Thus it is preferable to repress powder accumulation within deadman packed bed to keep its permeability. Increase in powder diameter raises the maximum value of volume fraction of powder within the deadman, and heavier particles tend to leave from the gas stream. Such particles are considered easy to accumulate in the deadman. Therefore decrease in generation of larger and heavier particles and increase in their consumption are effective to realize permeable deadman.

KEY WORDS: blast furnace; powder flow; deadman; simulation; mathematical model.

1. Introduction

With recent increase in pulverized coal injection rate into blast furnace through tuyere,1–5) powder behavior in the lower part of the furnace have been attracting technical and scientific interests. Sampling a part of packed bed within blast furnace through tuyere had been carried out in several blast furnaces and raceway combustion simulators,6–12) and it revealed the packing structure on tuyere level. Although the powder motion in the lower part of the furnace was estimated from this information, such sampling must be done when the feeding of blast is stopped or much reduced, and gives insufficient information to reconstruct multi-dimensional flow behaviors of gas and powder. Although modern blast furnaces have number of sampling probes, experimental determination of packing structure and flow behaviors of gas and powders under actually operating condition is costly and with technical difficulties. Another method to determine such behaviors is simulation based on fluid mechanics. For this method fundamental flow mechanisms need to be formulated. Powder motion in packed bed had researched by several research groups to clarify traveling velocity of powder,13–15) interaction force between powder and packed particles,16–21) distribution of powder hold up22–25) and powder deposition behavior,26,27) and their results were applied to simulate powder behavior28–31) in shaft furnace, blast furnace mid zone, and so on. However, the effects of deadman structure and powder properties on powder and gas flows in the lower part of the blast furnace has yet to be discussed.

Under large pulverized coal injection rate condition, not only unburned char but also fine coke particles increases in lower zone of blast furnace.32) Char is solid residue after volatile combustion of pulverized coal, and its diameter is usually in the comparable range with one of original pulverized coal. The coal particle releases gaseous combustibles and changes its structure to porous during volatile combustion process, and apparent density of char particle is generally low. Contrarily the fine coke is fragment of charged coke, and some of the particles have larger diameter and density compared with the unburned char particles. It is known that the particle diameter and density has large effects on the motion of particle entrained in a fluid. Therefore it is expected that the particles having different properties show different flow characteristics also in the blast furnace. Flow behavior of the powder is one of the im-
important parameters in the formation of packed structure because a part of the flowing powder accumulates in the packed bed.

In this study numerical simulations on flow behavior of gas and powder phases were performed to clarify the effect of packing condition of deadman and particle properties in the lower part of blast furnace by using a mathematical model of four phase flow and heat transfer in blast furnace.\(^{33}\)

2. Method of Calculation

2.1. Mathematical Model

The mathematical model for flow and heat transfer in blast furnace used in this study handles gas, solid, liquid and powder as different phases. The model consists of conservation equations of mass, momentum and thermal energy for all considered phases in steady state and axisymmetric configuration, and exchange of mass, momentum and heat among different phases are taken into account in the conservation equations. Inter-phase exchanges of momentum and heat respectively due to velocity and temperature differences are evaluated using previously reported correlations.\(^{33}\) This model uses simplified reaction-rate descriptions and they are determined by temperature range with equilibrium limitations. Therefore, mass and heat exchange rates due to reactions and reaction heats are given based on this simplified formulation. The details of the mathematical model, boundary conditions and numerical implementations are described in the previous study.\(^{33}\) This model gives two dimensional flow and temperature fields and distributions of volumetric fractions for all phases in vertical cross section including center axis of the furnace as well as overall operation parameters.

2.2. Calculating Conditions

This model was applied to the analysis of blast furnace having 4 907 m\(^3\) of inner volume operated at 8 747 Nm\(^3\)/min of blast volume and 2.19 thm/m\(^3\)/d of productivity. Operational data used as the input data for the model calculations are summarized in Table 1. The furnace was operating with stack reduction efficiency of 92.6%, utilization ratio of carbon monoxide of 49.5% and degree of direct reduction of 29.3%. The furnace geometry and calculation grid are shown in Fig. 1. The volumetric ratio of ore to coke and particle diameters at the burden surface are shown in Fig. 2. In the standard condition coke diameter in the deadman is assumed uniform and 30 mm, and the voidage is set at 0.509.

Four series of calculations were performed as explained as follows.

1. Effect of coke particle diameter in the deadman zone was examined. Four diameters, namely 15, 20, 30 and 40 mm, were tested. In this case voidage of the deadman varies according to the following equation\(^{34}\)

\[e_{\text{DM}}=0.724+0.153 \log_{10} d_{\text{coke}} \]  \( (1) \)

and changes from 0.445 to 0.510 in the above diameter range. In this equation, \(e_{\text{DM}}\) and \(d_{\text{coke}}\) are voidage and coke diameter in deadman zone, respectively.

2. Deadman voidage was changed 0.15, 0.20, 0.30, 0.40 and 0.45 while coke diameter was constant.

3. Pulverized coal injection rate and combustion efficiency were set at 150 kg/thm and 75%, respectively. Diameter of unburned char was assumed 0.1, 0.5, 1.0, 2.0 and 3.0 mm. The assumed texture of the unburned char is balloon type and swelling factor for the standard case (0.1 mm) is about 1.5. Thus the density of unburned char was assumed 100 kg/m\(^3\) and this value is also used for the other diameters.

<table>
<thead>
<tr>
<th>Table 1. Operating conditions used in the simulation.</th>
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<tr>
<td>Hearth diameter</td>
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<td>Height of packed bed</td>
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<tr>
<td>Blast volume</td>
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<tr>
<td>Blast temperature</td>
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<tr>
<td>Oxygen enrichment</td>
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<tr>
<td>Pulverized coal injection rate</td>
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<td>Coke rate</td>
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<td>Ore rate</td>
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<td>Top pressure</td>
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Fig. 1. Grid arrangement.

Fig. 2. Burden distributions.
4. The density of generated powder was increased 10 times as original case (1,000 kg/m³) while the generation rate was constant. Same diameters as preceding case were examined.

2.3. Method of Evaluation

The model calculates two-dimensional distributions of process variables, such as velocity component, pressure, temperature, and so on, as well as overall operation parameters. To evaluate effect of deadman structure and particle properties on flow characteristics of gas and powder phases, following parameters were obtained by processing calculated two-dimensional distributions.

1. Depth of 2,473 K isotherm from tuyere nose at tuyere level. This horizontal extent is called “penetration”.
2. The maximum penetration of 2,473 K isotherm from tuyere nose, and the height at which the maximum penetration is given.
3. Ratio of gas flow rate passing through deadman to total gas releasing rate from raceway zone.
4. Ratio of powder flow rate passing through deadman to entire flow-out rate from raceway.
5. The maximum value of powder volume fraction in deadman.
6. Pressure drop between burden surface and tuyere nose.

3. Results and Discussion

3.1. Base Case

Mass flux vectors of gas and powder phases, distributions of gas temperature, volume fractions of powder and liquid phases calculated under base condition are depicted in Fig. 3. Locations of deadman surface and cohesive zone are shown by dashed line, and raceway boundary is drawn as circle in front of tuyere. The gas phase that is introduced through tuyere is released from the raceway zone to packed bed in the lower part of the furnace from raceway. A part of the gas phase released from upper boundary of the raceway flows upward while the other part, namely the gas released from bottom and end of the raceway, passes through the deadman zone and then flows upward. In the cohesive zone, ascending gas flow once turns into horizontal direction due to existence of coke slits, which is described as anisotropic flow resistance in the mathematical model. After passing cohesive zone the gas changes its flow direction to upward again. In the stack region the gas phase shows central flow due to burden distribution, which more coke having higher permeability is charged onto central part.

The powder phase shows similar flow pattern to gas phase. The directions of most mass flux vectors are almost same as the gas vectors. But the magnitude of the mass flux vectors of both phases show different tendency. The gas phase disperses almost uniformly and ascending mass flux vectors show uniform distribution in the lower part of the furnace, and forms central flow in the stack region. On the contrary, the powder phase shows larger mass flux in mid-radial region throughout the furnace height. This powder flow pattern results in distribution of powder volume fraction, which also shows higher fraction in mid-radial region, as shown in Fig. 3(d). The powder phase undergoes strong friction from the solid phase, once it flows into the packed bed region from the raceway. Therefore the velocity of this phase decreases drastically in front of the raceway zone, and the volume fraction of powder increases in this region. Then powder in this dense area is entrained by upward gas flow, and then shows above-mentioned flow pattern.

The liquid phase generates in cohesive zone and flows downward. This descending flow is toward slightly outward due to friction with solid phase heading to raceway zone. Generally, the liquid phase tends to show higher volume fraction in outer region because the ratio of ore to charged materials increases with radial distance, especially just beneath the outer part of cohesive zone in which solid volume fraction is high. Around the raceway zone, liquid gets horizontal momentum due to interaction with gas phase that has high horizontal velocity component, and its flow direction turns once inward. The higher voidage in the raceway zone decreases flow resistance to liquid flow, thus the volume
fraction of powder in the raceway zone decreases. In the deadman zone, liquid volume fraction decreases with going down because the liquid temperature increases mainly due to heat exchange with solid phase, and liquid viscosity decreases with this temperature rise, that results in higher liquid descending velocity.

Regarding to the gas temperature, it shows the maximum around the raceway end zone due to the combustion of coke and pulverized coal. The high temperature region surrounded by 2473 K isotherm shows almond nut shape. The gas temperature decreases with ascending in the furnace mainly due to heat exchange with solid phase. In the cohesive zone, exchanged heat from gas to solid is consumed as melting latent heat, cooling rate of gas phase gets quicker.

In the stack region, central gas flow forms and cone shape temperature distribution is formed. In the wall region, gas temperature increases because increase in gas flow rate due to burden distribution and assumption of adiabatic wall.

The evaluation parameters for this standard condition are follows. The penetration of high temperature gas at tuyere level and the maximum penetration are 2.86 and 3.50 m, respectively, and the height of maximum penetration is 3.28 m. Flow ratios of the gas and the powder phases are 45.1 and 72.7%. The maximum powders volume fraction in the deadman is 0.096%, and the average liquid temperature at tuyere level is 1751 K.

### 3.2. Effect of Deadman Coke Diameter

Figure 4 compares gas temperature distributions calculated for various deadman coke diameter. The coke diameter is decreased from 40 (a) to 15 mm (d). The high temperature region surrounded by 2473 K isotherm shrinks with decrease in deadman coke diameter. However, deformation of this region is small. This is considered that the deadman voidage for the smallest coke diameter case (15 mm) is still 0.445, and decrease in deadman permeability is small. The deadman cools with decrease in deadman coke diameter. The isotherm of 2273 K encroached into the deadman region in smaller diameter cases, namely 20 and 15 mm. On the contrary, the deadman coke diameter has small effect on the temperature distribution in the upper half of the furnace is small. In Fig. 4(d), slightly higher temperature region appears in the central bottom region. This temperature increase is caused by numerical instability due to accumulation of powder in central bottom numerical grid. Although this phenomenon is observed in some other cases with low permeable deadman, it is confirmed that its effect on overall calculation results is small.

Figure 5 shows the variations of evaluation parameters with deadman coke diameter extracted from calculated distributions of process variables. Both the maximum and tuyere-level penetrations of hot gas into deadman and maximum penetration height monotonically increases with increase in deadman coke diameter in accordance with variation of high-temperature region shape. The maximum volume fraction of powder phase in deadman and overall pressure drop decrease with increase in deadman coke diameter. These trends are brought by the decrease in friction forces in deadman packed bed. The flow ratios of gas and powder also monotonically decrease with decrease in deadman coke diameter, and pressure drop through the furnace increases. Average liquid temperature on the tuyere level increases with decrease in deadman coke diameter. The mathematical model does not take into account the distribution of liquid at packing boundary at which packing structure changes. Thus the liquid that reaches to the deadman surface flows into deadman. The smaller diameter coke has higher flow resistance to the liquid flow and elongate liquid residence time in deadman. At the same time the contact area between the liquid and the solid phase also increases. Consequently the average liquid temperature rises with decrease in deadman coke diameter.

### 3.3. Effect of Deadman Voidage

Effect of deadman voidage on gas temperature distribution under constant deadman coke diameter condition is shown in Fig. 6. Similar to the previous case, the high temperature region tends to shrink. Contrarily the deformation
of this region is large, and encroachment into the deadman zone decreases. The deadman temperature lowers with decrease in deadman voidage. This tendency is more remarkable than deadman coke diameter, and a region in which temperature is lower than 1873 K appears when deadman voidage is set at 0.15. The variations of evaluation parameters are shown in Fig. 7. Similar to the previous case, both the maximum and tuyere-level penetration and height of the maximum penetration tend to decrease with decrease in deadman voidage, but the maximum penetration height increases in the minimum voidage case (ε=0.15). The deformation of high temperature region shown in Fig. 7 results in this rise of the maximum penetration height. Although pressure drop shows similar trend to the previous case and decreases with increase in deadman voidage, the maximum volume fraction of powder phase in the deadman decreases with decrease in deadman voidage. The ratios of gas and powder passing through deadman zone decreases with decrease in deadman voidage, and its effect is more significant than one of deadman coke diameter. Less than 10 per-
3.4. Effect of Char Diameter

Variations of temperature and powder volume fraction distributions with char diameter are shown in Figs. 8 and 9. The shape of high temperature zone deforms to “L” shape with increase in char diameter. The concentration of powder in the furnace increases with char diameter due to increase in friction between powder and lump solid phases. As explained previously the powder phase shows the maximum volume fraction in the region just beside the raceway zone. In 3.0 mm of char diameter case, the maximum volume fraction reaches about 2.8 percent as shown in Fig. 11. This large powder hold-up raises the flow resistance to the gas phase and generates non-uniform gas flow distribution on the raceway boundary. Distribution of mass flux of gas phase around the raceway zone is shown in Fig. 10. The dashed lines in this figure are 0.6 and 1.2% contour lines of powder volume fraction. The mass flux contours of gas phase deform downstream of high concentration region of powder phase. The gas flux contours are distorted toward tuyere side between deadman surface and tuyere axis, and this region almost coincides to the area in which the powder volume fraction is larger than 0.6%. This deformation is significant just inside the dense powder region (more than 1.2% of volume fraction). This deformation of the mass flux contour implies weakened gas flow in this region. This variation of gas flow decreases thermal energy transport to the downstream of dense powder zone, and the high temperature region deforms to “L” shape.

Figure 11 shows variation of the evaluation parameters. The penetrations of high temperature gas flow show small changes with char diameter regardless of deformation of high temperature region. Contrarily the height of the maximum penetration lowers with increase in char diameter due to the deformation. The pressure drop increases with the char diameter when the char diameter is lower than 1.0 mm, and shows slight increase in larger char diameter range. The maximum volume fraction of powder phase in deadman increases with char diameter. Ratio of gas flow rate passing through deadman shows little change with char diameter. The coke diameter and voidage in the deadman zone in this series are 30 mm and 0.491, respectively, and this region has sufficient permeability. Thus variation of gas flow rate passing through deadman is small while the temperature distribution is affected by the increase in powder hold-up. When the char diameter becomes larger than 0.5 mm, more than 90 percent of the powder goes into deadman zone. The inertia of fine particle increase with char diameter due to the mass of single particle also increases with its diameter, most powders moves horizontally until it gets into deadman zone.
3.5. Effect of Fine Coke Diameter

Effect of fine powder diameter is examined for heavier particles assuming fine coke. The density of the powder tested here is 1000 kg/m³ while previous case uses 100 kg/m³. Although the fine coke diameters up to 3.0 mm were tested in this series of calculation, the mathematical model gave results with insufficient accuracy (large computation residual error) when the particle diameter exceeded 1.0 mm. Figures 12 and 13 show the distributions of gas temperature and powder volume fraction. The diameter of heavier powder has similar effect to char diameter, and high temperature region deforms to “L” shape. In the smaller particle cases the distribution of powder hold-up shows similar trend to the previous cases. Contrarily most larger particles that get into the deadman is unable to be entrained by upward gas flow in the deadman, and they head to downward. The mathematical model used in this study takes into

![Fig. 8. Effect of char diameter on gas temperature distribution.](image1)

![Fig. 9. Effect of char diameter on distribution of powder volume fraction.](image2)

![Fig. 10. Distribution of mass flux of gas phase for char diameter of 3.0 mm. (Unit: kg/m²s)](image3)
account only dynamic powder hold-up, and this artificial powder accumulation at the bottom of the furnace causes numerical instability mentioned above. This trend, however, indicates that heavy and large particles is possibly to deposit in the deadman zone.

3.6. Discussion

First case examined the effect of the deadman coke diameter while voidage varies with diameter, and second one tested the effect of deadman voidage under constant coke diameter. Both parameters have similar effect on most calculation results, and voidage has stronger effect. This points out that the decrease in coke diameter within the tested diameter range due to reaction (solution loss, direct reduction, carburization, and so on) is tolerable issue for the deadman permeability. Contrarily decrease in voidage due to accumulation of unburned char, fine coke, molten materials, etc. lowers the deadman permeability even the particle diameter is kept enough large.

Regarding to the lighter particle, the diameter of generat-
ed powder has strong effect to the volume fraction of powder phase although the powder flow pattern shows slight change with particle diameter. Pressure drop in the furnace rises with powder diameter especially in the smaller diameter range, and its effect gets smaller for larger diameter. The maximum volume fraction of powder in the deadman zone, however, increases even for the larger diameter range. This increase in volume fraction is considered to raise the chance for such larger powder to deposit in the deadman zone. Thus this suggest that the deadman permeability could be deteriorated by the static powder hold-up when larger particles are generated. The density of the generated powder has great effect on the powder flow pattern especially for larger particle. Most generated particles flow downward in the deadman zone getting away from ascending gas stream when their diameter becomes larger than 1.0 mm. Such descending powder is considered to accumulate and worsen the deadman permeability. Thus it is considered important to decrease fine coke generation and to increase its consumption to keep permeable deadman.

4. Conclusions

This study performed numerical experiments on effects of deadman structure and properties of generated powder on gas and powder flow behavior in the lower part of blast furnace by using two-dimensional axisymmetric mathematical model for flow and heat transfer in blast furnace. The series of mathematical simulation revealed that:

1) Among the properties describing structure of deadman packed bed, voidage has greater effect than coke diameter on penetration of high temperature gas and powder into the deadman zone and pressure drop in the furnace. The deadman having extremely low voidage is possibly to cause formation of low temperature zone in the deadman. Thus it is preferable to repress powder accumulation within deadman packed bed to keep its permeability.

2) Increase in powder diameter raises the maximum volume fraction of powder within the deadman, and heavier particles tend to get away from the gas stream. Such particles are considered easy to accumulate in the deadman. Therefore decrease in generation of larger and heavier particles and increase in their consumption are effective to realize permeable deadman.

(3) For more detailed analysis, static hold-up of powder and liquid dispersion are necessary to be taken into account.

REFERENCES