Influences of Physical Properties of Particle in Discrete Element Method on Descending Phenomena and Stress Distribution in Blast Furnace

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Recently, discrete element method (DEM) had been applied for simulation of the blast furnace. For mitigating computation load and precise simulation of blast furnace, the determination of optimum physical parameters in DEM are very important. In the present study, influence of variation of hardness, rolling friction coefficient of particle and descending velocity on the solid flow and stress distribution in the blast furnace were investigated. Decreasing hardness of particle does not affect on shape of layers descending in the shaft, and causes acceleration of computation. However, stream line of particles and stress distribution vary with changing in hardness of particle. The softening of particle is not suitable for analysis of stream line and stress distribution of packed bed in the blast furnace. Stream lines of particle become smooth with an increase in the rolling friction coefficient. The value of the rolling friction coefficient should be controlled for representing shape of actual burden. It is confirmed that descending velocity of burden also affects on the stress distribution of the packed bed. Physical properties and calculation condition should be optimized depending on the purpose of analysis and phenomena in the blast furnace.

KEY WORDS: discrete element method; mathematical modeling; blast furnace; ironmaking; stress distribution.

1. Introduction

Blast furnace has been enlarged to increase the productivity. Blast furnaces over 5,000 m³ need well controlled burden charging and material flow inside it. Recently, global warming is taken as a serious issue, and then low reducing agent operation of blast furnace is desired for the ironmaking field. Enlargement of blast furnace and the operation with low reducing agent occasionally cause biased and unstable gas and solid flow. Then, that leads the discontinuance phenomena such as making unstable slip of burden and fluctuation of the blast pressure. In order to prevent causing the discontinuance phenomena and control the blast furnace more accurately, detailed understanding condition of in-furnace is important.

Mathematical models for the blast furnace operation based on the equations of mass, momentum and heat balances and reaction kinetics have been developed.1, 2) The behaviors of gas, liquid, solid and fine coke particle flows and distribution of temperature and reaction degree are able to be estimated by continuum-based models. The discontinuance phenomena and the microstructure of a particulate bed, however, could not be simulated with the previous models. In recent years, discrete element method (DEM) is applied to simulate the solid flow in the blast furnace.3-7) If practical conditions were applied for the simulation, DEM would offer the descending behavior for each particle of burden in the furnace accurately. Distribution of stress and vacancy in packed bed, and velocity and stress of each particle can be drawn from the result of calculation. Meanwhile, the number of burden particles in the blast furnace is much larger than the computation capacity. In order to reduce computation load, some techniques were used to be applied. Properties of particle such as size, hardness, and frictions were controlled. Motion of packed bed was accelerated. Natsui et al. had discussed the influence of acceleration and variation of size on the solid motion in the shaft.8) Many researchers had investigated solid motion of packed bed with soften particle, however influence of variation of the conditions is unclear.

In the present study, influences of hardness and rolling friction of DEM particles on descending phenomena and stress distribution in packed bed of the blast furnace are investigated.

2. Discrete Element Method for Blast Furnace

2.1. Fundamental Equations of DEM

Concept of interactive force between particles calculated in DEM is illustrated in Fig. 1. Translational and rotary motions of each particle are decided by the contact force between particle and wall, and particle and particle. As
shown in (b) and (c) in Fig. 1, a model of contact force which consists of the Voigt model including a spring and dashpot was used for the DEM. The contact forces, $F_{n,ij}$: normal and $F_{s,ij}$: shear are derived as

$$F_{n,ij} = \left( K_n \Delta u_{n,ij} + \eta_n \frac{\Delta u_{n,ij}}{\Delta t} \right) n_{ij} \tag{1}$$

and

$$F_{s,ij} = \left( K_s (\Delta u_{s,ij} + \Delta \phi_{ij}) + \eta_s \frac{(\Delta u_{s,ij} + \Delta \phi_{ij})}{\Delta t} \right) t_{ij} \tag{2}$$

Where, $K_n$, $\eta_n$, $\mu_n$, $n$ and $s$ denote stiffness, damping coefficient, friction coefficient, normal and tangential, respectively. $\Delta u_{n,ij}$ and $\Delta \phi_{ij}$ are a relative translational displacement of gravitational center between particle $i$ and $j$, and a relative displacement at the contact point due to rotation of particles, respectively. $n_{ij}$ and $t_{ij}$ are unit vector from particle $i$ to $j$ in normal and tangential directions. The spring and dashpot represent the elastic and plastic nature of particles, respectively.

In the tangential direction, slider which expressing the maximum friction force on particles, was installed as Eq. (3). When the shear force is larger than maximum contact force, following value is employed as shear force.

$$F_{s,ij} = \mu F_{n,ij} t_{ij} \tag{3}$$

$K_n$ and $K_s$ is derived from Young’s modulus ($E$) and Poisson’s ratio ($P$) as

$$K_n = \frac{2b \cdot E}{3(1-P^2)} \tag{4}$$

$$K_s = \frac{K_n}{2(1+P)} \tag{5}$$

where, $b$ denotes radius of contact circle.

The motion of particle is derived from integration of force $F$, gravitational acceleration $F_g$ and, moment caused by the tangential force $M$.

$$m \frac{dv}{dt} = \sum F + mF_g \tag{6}$$

and

$$I \frac{d\omega}{dt} = \sum M \tag{7}$$

Where, $m$, $v$, $I$ and $\omega$ denote the mass of the particle, velocity, moment of inertia and the angular velocity, respectively.

In order to represent shapes of coke and ore, rolling friction which mitigate the shear stress acted on contact circle, was installed. Rolling friction: $M_r$ is defined as a function of rolling friction coefficient, such as,

$$M_r = \frac{3}{8} \alpha \cdot b \cdot F_{s,ij} \tag{8}$$

where, $\alpha$, $b$ and $F_{s,ij}$ are rolling friction coefficient, radius of contact circle and normal force, respectively.

As described above, DEM is composed of small number of fundamental equations and parameters. The motion of particle is controlled by property of particles such as hardness and friction.

### 2.2. Condition of Model

Solid motion in a blast furnace of 5000 m$^3$ inner volume with 40 tuyeres is object for the present DEM simulation. The individual particle of burden is represented by a solid sphere. Ore and coke have respective uniform diameters. The number of burden particle in the blast furnace is much larger than capable number for handling by the present three-dimensional DEM. In order to lessen the number of particles, a particle in present calculation is considered to represent a cluster of burden particles. Thus, the diameters of particle were increased to 0.12 m and 0.24 m for the ore and coke in simulation, respectively. In order to decrease calculating volume, blast furnace was also cut out between an angle of 18 degree as shown in Fig. 2. The angle of sector form is 18 degree, and the both side of flat walls are supposed to be connected with the periodical boundary condition. Raceways are placed each 9 degree on the wall. Two tuyeres are located on the flat wall and one is on center of curved wall. Shape of blast furnace for the present DEM simulation is shown in Fig. 3. The radiiuses of the blast furnace of tuyere level and belly and angle of bosh are 7.8 m, 8.6 m and 78 degree, respectively. In order to avoid self contact of particle, cylindrical wall (shadowed region) with 1.2 m diameter and no friction was pleased at center of the blast furnace. The tap hole is placed at 4.5 m over bottom of blast furnace. The buoyancy effect of hot pig iron is taken into account in the present simulation. Multi-layered packed bed structure composed of ore and coke is composed by putting the burden layer by layer. Ore particles start to shrink and melt down at top and bottom of meting zone, respectively. The stock line is placed at 25 m over the tuyere level.

The raceway shape is assumed to be the ellipsoidal shape with 1.5 m in length and 1.0 m in width. The particle entrained the raceway area is uniformly vanished for an aimed interval. A part of coke particle is disappered near the wall at the taphole level. That represents combustion of coke.
and dissolution of coke in to the hot metal.

Generally, the gas flow has an influence on the burden descending, however it is not clear that the gas flow has an influence on the burden descending. In the present study, the physical mechanism through the interaction among the particles is regarded as of major importance for analyzing the burden descending.

3. Influence of Physical Properties of Particle on Solid Behavior in Blast Furnace

3.1. Physical Properties of Particle which represent Actual Burden

If the optimum conditions on the particle are chosen, the DEM would show the fact of solid motion. Particle handled in the DEM is represented as a sphere. However the actual burden used in blast furnace is disorder in the shape and physical properties, namely, relative density, size, hardness, contact friction coefficient, and rolling friction coefficient. The size and charging rate of burden are decided according to the limit of calculation. The friction coefficient between coke and coke is measured in the previous study. A lump of coke was cut and flat surfaces were made by grinding. Flat surface was contacted each other, and then the force for sliding one piece of coke was measured. Comparing the force and weight of the piece of coke, the friction coefficient was determined as 0.76. Friction coefficients between coke and fire block, and ore and block were around from 0.7 to 1. Therefore 0.76 was used as friction coefficient. The motion of burden in DEM is much faster than that in actual blast furnace. Maximum time step is limited by the hardness and size of particles. Standard condition of calculation is summarized in Table 1. Hardness, rolling friction coefficient and discharging rate of particles were varied. The effects of them on descending phenomena are discussed in the following part.

3.2. Influence of Hardness of Particle on Stress Distribution and Solid Flow

The DEM analysis requires large computing resources and computing time because it tracks positions, velocities and force balances of a huge number of particles. The time step of the calculation is constrained by the physical properties of the particles. Thus appropriate adjustment of the physical properties and conditions might reduce computation time without deteriorating simulation accuracy. The lower hardness of particle allows the longer interval of calculation steps, meanwhile it does not increase number of active particle significantly, and then that causes acceleration of DEM simulation. Influence of particle hardness on the simulation was studied. The Young’s modulus was decreased from 5.0 to 0.2 GPa. Figure 4 compares layer shapes obtained under various Young’s modulus. The rolling friction coefficient was a constant value. Solid circles and open gray circles indicate ore and coke particle, respectively. Thickness of the layers decreases gradually with descending. The shape of layers, however, shows unremarkable change. Hardness of particle does not affect the descending behavior of the layers.

Figure 5 shows average velocity of particles between the bottom of hearth and 3 m below the stock line in the blast furnace with various Young’s modulus that is calculated by DEM. The variations of velocity of 5.0 and 2.0 GPa are similar each other. Due to charge of iron ore peaks are seen periodically. Short term variation is seen between them. However, short term oscillations are not clear for the result of 0.2 GPa. Magnitude of fluctuation is increased with 0.2 GPa in Young’s modulus. Descending behavior varied with decreasing hardness of particle to 0.2 GPa.

Stream line of particle is shown in Fig. 6. Young’s modulus of the particle was varied from 5.0 to 0.2 GPa. Five particles were chosen randomly, and traced the position. The motion is smooth in the shaft level, however the motion become irregular below the cohesive zone. Especially, irregularity increase with an increase in the hardness.

The Young’s modulus of the actual coke has the range of 5–10 GPa in the room temperature before reaction. However, some part of coke is reacted in shaft and below the melting zone, thus the hardness of coke might change the behavior of reaction and descending. It is difficult to obtain desirable value of hardness in high temperature. For more accurate analysis, relationships between reaction ratio and harness, and position and reaction ratio should be installed.

Normal stress of particle with various hardness is shown in Figs. 7 and 8. In Fig. 7, each circle and its color denote position of particle and the extent of stress, respectively.
The stress is derived by summation of forces at all contact point of a particle and then divided by surface area of the particle. Fig. 7(a)–7(d) are 5.0, 2.0, 0.5, and 0.2 GPa in the Young’s modulus, respectively. However the stress is a momentary value, stress distribution does not change significantly,11) therefore the figure would be a representative distribution of stress. Center of blast furnace around the tuyere level show high stress region, and the stress on the particle is over 3 MPa. Stress network is not clearly observed from the figure. It can be seen that the hardness of particles affect on the stress distribution. Influence of hardness is also seen in Fig. 8, distribution of stress is spread with the harder particles, and extent of the stress variation is averaged with a decreasing in the hardness.

3.3. Influence of Rolling Friction of Particle on Stress Distribution and Solid Flow

In order to represent the actual burden flow in the blast furnace, physical property of the particle shape used in the simulation would be important. Actual ore and coke are not smooth spheres, therefore a concept of rolling friction14) is introduced for represent shape of actual burden, and that is defined as Eq. (8).

The rolling friction coefficient is a parameter that works as resistance to the particle movement of rotation. The rolling friction is related to hardness and diameter, there-fore the rolling friction coefficient is valid for the particles in same physical condition.

Mio et al. reported that distributed rolling friction coefficient were employed for representing the ore movement at the charging.6) However, the influence of rolling friction coefficient on solid motion in packed bed is not clear.

Natsui et al. had calculated the influence of the rolling friction on motions of coke particle and packed bed in front of tuyere. Height of stagnant zone increase with an increase in the rolling friction parameter.10) In the study, following tendencies were seen; height of stagnant zone increased with an increase with rolling friction, however the velocity of particle varied with charging and slips in short time, then the stagnant zone could not be indicated precisely.

Variation of average speed of all particles every 0.1 s is shown in Fig. 9. The motion of solid in DEM simulation is much faster than actual motion of burden because the computations are artificially accelerated by quicker elimination of particles from raceway. In this simulation, particles descend from the burden surface to the tuyere level in about 60 s, while it takes about 6 h in actual blast furnace. Due to the impact of charge, active periods are seen. Short term vibrations are also seen between the large fluctuations. There is no obvious difference among the motions with $\alpha=2, 5, 10$ and 20. Though, it seems that lower rolling friction may cause the regular period alternation. Although influence of changing the rolling friction in ten times is seen in distribution of velocity and motion of particles, it is not remarkable in a packed bed.

Stream lines of particle with various rolling frictions are shown in Fig. 10. The particles were randomly chosen. Rolling friction was varied from 1.25 to 20. The motion is smooth in the shaft level, however the motion become irregular below the cohesive zone. Especially, irregularity increase with a decrease in the rolling friction.

Normal stress of particle with various rolling friction is shown in Fig. 11. Each circle and its color denote position of particle and the extent of stress. The stress is derived by summation of forces at all contact point of a particle and then divided by surface area of the particle. Fig. 11(a)–11(e) are 1.25, 2.5, 5.0, 10, and 20 in the rolling friction coefficient, respectively. In Fig. 11(a), high stress region is seen over raceway, meanwhile, it is restricted only small region. Stress distribution of others are similar each other. Influ-
ence of changing the rolling friction on the stress distribution is not remarkable. Variation of rolling friction affect on the solid motion around deadman, however, do not affect on stress distribution, significantly.

3.4. Influence of Descending Velocity on Stress Distribution

In the simulation in previous section, particles descend from the burden surface to the tuyere level in about 60 s, while it takes about 6 h in actual blast furnace. In order to mitigate the computation load, the solid motion in the blast furnace simulation in DEM is used to be accelerated. Natsui had investigated the influence of acceleration in DEM on motion of particle in packed bed.8) In the study small scale model of blast furnace, and single size particle are employed. Variation of descending velocity of the packed
bed does not affect on the shape of tracer layer. However, microscopic motion of each particle changes with a changing in descending velocity. In order to analyze motion of each particle, the descending velocity should be considered.

Here, influence of descending velocity on stress distribution is studied. Normal stress of particle with various descending velocity is shown in Fig. 12. Fig. 12(a)–12(e) are accelerated about 0, 90, 180, 360 and 720 times velocity of burden in actual blast furnace, respectively.

Total stress distributions are almost similar to each other. However the stress over the raceway decreases with an increasing in descending velocity. Solid flow in the region over raceway is faster than other position. Fast flow causes sliding between particles and the slide weaken the stress pass. Therefore the difference of stress distribution is seen in high velocity region, namely, near the raceway. However, comparing (a), (b) and (c), the stress distribution is not significantly, thus it can be said that the stress distribution in the blast furnace can be simulated in accelerated condition up to some extent.

4. Conclusions

DEM is applied for simulating solid motion in the blast furnace. In the present study, influences of hardness and rolling friction of particles, and acceleration of solid motion on results of calculation such as descending phenomena and stress distribution in packed bed of the blast furnace are investigated. Following results were obtained.

Accelerating the motion of particles and decreasing hardness which allows prolonging the time step, mitigate computation load. Macroscopic motions of particle in the packed bed dose not change with varying in the parameters. Meanwhile, hardness, rolling friction and descending velocity affect on the behavior of solid motion. Motion of particle in lower part of the blast furnace become smooth with a decrease in hardness of particle. Stress distribution is averaged with a decrease in hardness of particle. Short term oscillations become not clear with a decrease in hardness of particle. Variation of rolling friction does not affect on stress distribution, significantly. However, the motion of particle becomes smoothly with an increase in rolling friction. Acceleration of descending velocity slightly affect on the stress distribution. Especially, transition of stress is weakened in high velocity region, and stress network is not seen over the raceway.

REFERENCES

1) J. A. Castro, H. Nogami and J. Yagi: *ISIJ Int.*, 42 (2002), 44.
2) H. Nogami, M. Chu and J. Yagi: *Comput. Chem. Eng.*, 29 (2005), 2438.
3) P. A. Cundall and O. D. L. Strack: *Geotechnique*, 29 (1979), 47.
4) K. Nakano and H. Yamaoka: *Tetsu-to-Hagané*, 92 (2006), 939.
5) T. Nouchi, T. Sato, M. Sato and K. Takeda: *Tetsu-to-Hagané*, 92 (2006), 955.
6) H. Mio, K. Yamamoto, A. Shimosaka, Y. Shirakawa and J. Hidaka: *ISIJ Int.*, 47 (2007), 1745.
7) Z. Zhou, H. Zhu, A. Yu, B. Wright, D. Pinson and P. Zulli: *ISIJ Int.*, 45 (2005), 1828.
8) S. Natsui, S. Ueda, Z. Fan, J. Kano, R. Inoue and T. Ariyama: *Tetsu-to-Hagané*, 96 (2010), 1.
9) T. Kawaguchi, S. Nishi, T. Tanaka and Y. Tsuji: 1993 Syunki-Kenkyuhyoukai-Kouen-Youshi, Soc. Powder Technol. (Jpn.), Kyoto, (1993), 106.
10) S. Natsui, S. Ueda, M. Oikawa, Z. Fan, J. Kano, R. Inoue and T. Ariyama: *ISIJ Int.*, 49 (2009), 1308.
11) S. Natsui, S. Ueda, Z. Fan, N. Andersson, J. Kano, R. Inoue and T. Ariyama: *ISIJ Int.*, 50 (2010), 207.