Modeling of Solid Particle Flow in Blast Furnace Considering Actual Operation by Large-scale Discrete Element Method

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The objective of this paper is to analyze the solid particle flow in a blast furnace having bell-type charging system by using large-scale Discrete Element Method (DEM). About 500,000 particles were calculated in this work. The particle discharging behavior of laboratory-scale blast furnace was compared to confirm the material properties used in the simulation work, and the simulated trajectories of tracer particle correlated with those of experimental very well. The melting behavior of iron ore and combustion of coke in the actual blast furnace were modeled by shrinking particles. The simplified bell-type charging system in this simulation mimicked the actual blast furnace, the collapse of coke layer at the top was observed, and the time change of stock level was quite similar. The particle pulsating flow was observed at the upper area of blast furnace, and the descending velocity near side wall was much larger than that of center in this calculation. The melting position of ore was mapped and the most of iron ore were melting above the raceway. This area should be cohesive zone. This modeling is the first step of the analysis of blast furnace by using Discrete Element Method. Although only contact force was considered and simplified melting zone or raceway were introduced, this large-scale simulation has a high potential to analyze the solid flow in the blast furnace, and the abnormal phenomena or serious problem in blast furnace operation will be analyzed in the future by considering gas flow or heat transfer.

KEY WORDS: blast furnace; discrete element method; large-scale computing; burden descending; ironmaking.

1. Introduction

Granular materials are used in many industry fields, such as chemical, material, pharmaceutical, agricultural, steel industries, and so on. Controlling their flows or several phenomena in each process are very important to operate with high efficiency or stability, because their behavior and characteristics are being changed continuously. That’s certainly the case of blast furnace operation in an iron-making process. A blast furnace is a huge reactor having about 5,000 m³ for producing pig-iron from ore particles. Iron ore (sintered ore and pellet) and coke particles are stacked alternately in layer, and the gas having high temperature is blown from tuyeres. Iron ore particles are reduced during descending, and many physical changes and chemical reactions between each phase are undergoing in there. Thus, it is extremely complicated system, and the abnormal phenomena or serious problem are sometimes happened. Therefore, to grasp the cause-and-effect is very important issue for stable operation. The dissection of blast furnaces had been carried out,1–3) and they had given a lot of useful information. Several researches had been also investigated experimentally4–7) and some mathematical models had been proposed.8–10) However, it is necessary to analyze the individual solid particle behavior in the blast furnace to know the several phenomena in more detail.

Discrete Element Method (DEM)11) is one of the most famous and reliable simulation methods for an analysis of solid particle behavior, and an approach from the computational simulation based on DEM is useful to grasp the phenomena found in the blast furnace operation. Some studies on the modeling of solid flow in blast furnace had been already reported.12–16) The analysis of the part of blast furnace, mostly around the raceway, was investigated by considering the large particle size ratio, however, it has been hard to simulate both iron ore and coke particles having large particle size ratio in whole blast furnace. Because the scale of blast furnace is huge and there are uncounted particles having different sizes even in the laboratory-scale blast furnace. It is also very important to consider the collapse of coke layer during charging. Thus, the coke and iron ore particles should have proper particle size ratio or material properties between them, and the charging process in the blast furnace operation should be modeled. The authors had achieved speeding up of DEM by optimizing the particle detection process17,18) and optimizing the program.19) This new DEM algorithm has a high potential to simulate the large number of particles.
In this paper, the solid particle flow in the blast furnace was modeled with taking into account the actual operation. The simplified bell-type charging system was mimicked, and the melting behavior of iron ore and combustion of coke were considered by shrinking particle in small steps. Only contact force was calculated, and the burden descending behavior was simulated. The material parameters used in the simulation work were also confirmed by comparing discharging behavior in a laboratory-scale blast furnace.

2. Experimental

Figure 1 shows a picture of laboratory-scale cutting blast furnace which was used in the experimental work, and its height, width or depth were 780, 402 or 130 mm, respectively. It had two orifices at the bottom, and its width was 45 mm. The coke (mass median diameter: 9.3 mm) and sintered ore (mass median diameter: 3.0 mm) particles were charged in layers. 29 tracer particles having about 22.0 mm in diameter were located between the layers. The tracers were numbered from the bottom to top and left to right; i.e. 1st one was leftmost tracer particle at the bottom, 5th one was rightmost at bottom, and 29th was rightmost one at the top layer. The discharging behavior of tracer particle was recorded by using the digital video recorder (DCR-PC300, Sony Corporation), and their velocities were measured from the recorded images.

3. Simulation

3.1. Discrete Element Method

The solid particle flow in the blast furnace was simulated by using large-scale Discrete Element Method (DEM).11,17–20) DEM consists of an idea of determining the kinematic force to each finite-sized particle. All forces acting on each particle are modeled and calculated at every discrete-time step. The trajectories of particles are updated by Newton’s law of motion.

\[
\begin{align*}
\dot{v} &= \sum_{m} F \\
\dot{\omega} &= \sum_{l} M 
\end{align*}
\]

Table 1. Material properties in simulation work.

<table>
<thead>
<tr>
<th></th>
<th>Coke</th>
<th>Iron ore</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young's modulus</td>
<td>5.4</td>
<td>35.0</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>0.22</td>
<td>0.25</td>
</tr>
<tr>
<td>Density</td>
<td>1050</td>
<td>3300</td>
</tr>
<tr>
<td>Frictional coefficient</td>
<td>0.51</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Where, \( v \) is a particle velocity, \( F \) is the summed force acting on a particle, \( m \) means the mass of a particle, \( \omega \) is an angular velocity, \( M \) and \( I \) denote the moment of force and the moment of inertia. The contact model between two particles is given by Voigt model, which consists of a spring-dashpot and a slider for the friction in a tangential component. The contact forces, \( F_n: \) compressive and \( F_t: \) shear, are calculated by following equations.

\[
\begin{align*}
F_n &= \left( K_n \Delta u_n + \eta_n \frac{\Delta u_n}{\Delta t} \right) n_{ij} \\
F_t &= \min \left\{ \mu \left| F_n \right| t_{ij}, \left( K_t \Delta u_t + \Delta \varphi_{ij} \right) + \eta_t \frac{\Delta \varphi_{ij}}{\Delta t} t_{ij} \right\}
\end{align*}
\]

Where, \( K \) and \( \eta \) mean the spring and the damping coefficients. \( \Delta u \) and \( \Delta \varphi \) are a relative translational displacement of gravitational center between two particles and a relative displacement at the contact point caused by the particle rotation. \( \mu \) is the frictional coefficient. \( n_{ij} \) and \( t_{ij} \) denote the unit vector from \( i \)-th particle to \( j \)-th one in normal and tangential components. The subscript \( n \) and \( t \) also denote the normal and tangential.

3.2. Comparison of Discharging Particle Flow with Experimental Work

The laboratory-scale blast furnace was modeled in the simulation work, and its configuration and size were same as those of experimental. The coke (mass median diameter: 9.3 mm, number of particles, \( n_{exp, coke} \): 31098) or iron ore (3.0 mm, \( n_{exp, ore} \): 450095) particles were stacked in layers. The frictional coefficient against the wall was 0.3, and \( \Delta t \) was 2.0 \( \mu s \). The materials properties used in the simulation were tabulated in Table 1. The particles were discharged from the orifices, and the descending velocities were calculated.

3.3. Modeling of Actual Blast Furnace Having Bell-type Charging System

The cutting model of blast furnace having bell-type charging system was used in this work, which is shown in Fig. 2. Its height, width and depth were about 10 m, 4 m
and 0.575 m, whose size were about one-third or quarter of actual blast furnace. The coke having 56.3–75.0 mm in diameter (Fig. 3, mass median diameter: 69.4 mm) and 25.0 mm of mono-sized iron ore were stacked in layer. Figure 4 shows the initial burden condition in the blast furnace, and the initial numbers of particles was 332336. The rectangular shape of raceway was considered, as shown in Fig. 5, and the coke particles in there dwindled to model its combustion behavior. The inverse V-shaped high temperature area, in which iron ore particles would be able to melt, was introduced, as shown in Fig. 6, and iron ore particles shrank in this area.

The particle sizes, \( D \), of coke or iron ore got smaller inversely proportional to their surface area at every calculation step, when the particles were in the raceway or melting zone.

\[
\frac{dD}{dt} = - \frac{R}{S} C_{\text{rand}} \tag{5}
\]

Where, \( R \) denotes the constant of shrinkage, \( i.e. \ R_{\text{coke}} = 6.37 \times 10^{-6} \text{ mm}^3/\text{s} \) and \( R_{\text{ore}} = 2.79 \times 10^{-7} \text{ mm}^3/\text{s} \). The reason why these values were used in this calculation is to balance between the shrinking rate and the charging rate. If the shrinking rate is much larger than charging rate, it is impossible to keep the stock level. However, these value should be related to chemical reaction, it will be considered in the future work. \( S \) and \( C_{\text{rand}} \) mean the surface area of particle and the random number (0–1.0), respectively. The random number was generated for all particles in the raceway or melting area.
melting zone at every step. Figure 7 shows the typical example of the time changes of particle size for coke or iron ore, which located in the raceway or melting zone. If the particle size became smaller than 5.0 mm, this particle was considered to be combusted or melted and excluded from the calculation. The excluded particles were used for coming charging process by the bell-type charging system. The stock level for charging was set at 700 mm from the bell. When the surface level became lower than the stock level, the particles would be charged from the bell (Fig. 8).

218.6 kg of coke ($n_{re, coke}$: 1159) or 572.3 kg of iron ore ($n_{re, ore}$: 21196) were charged in the blast furnace alternately. If the number of excluded particles were less than $n_{re, coke}$ or $n_{re, ore}$ when the charging process started, the new particles were generated in the calculation. Thus, the total number of particles was not constant. The discrete-time and total number of calculation steps were 5.0 $\mu$s and 12 millions steps, respectively.

4. Results and Discussion

4.1. Particle Discharging Using Laboratory-scale Blast Furnace

Figure 9 shows the relation between the distance from the center of initial particle position and the descending velocity of tracer particles at 4.55 s for the experimental and the simulation works. The velocities increase with increasing the distance from the center because the laboratory-scale blast furnace has two orifices near the side wall. The velocities around center also increase with increasing initial vertical position due to the formation of stagnant zone at the bottom. The descending velocities are asymmetric because of the distribution of the packing fraction in the laboratory-scale blast furnace leading from large particle size distribution. These tendencies are seen both in experimental and simulation results, especially, the degree of the asymmetric descending velocity in the experimental work seems to be larger than that of simulation, due to the particle shape. Figure 10 shows the descending velocities of 21st to 25th tracer particles at different time (1.66, 4.55 and 9.72 s). The velocity increases with time progresses, and simulated results correlated with experimental ones. Figure 11 shows the relation between the descending velocity and the discharging time for 17th and 27th tracer particles. The velocity increases with increasing discharging time and it shows somewhat pulsing motion. The time variation of descending velocity is quite similar during the discharging, although each data is not same. Figure 12 shows the picture and the snapshot of the heap after discharging. The shapes of heap are quite similar, and the angle of repose in experimental work is 50.5 degrees, and that in simulation is 49.0 degrees. It is found that these results correlate very well.

Fig. 7. Time changes of particle size when particle locates in raceway or melting zone.

Fig. 8. Schematic illustration of charging process by bell-type system.

Fig. 9. Relation between the distance from the center and the particle descending velocity at 4.55 s.

Fig. 10. Descending velocities of 21st to 25th tracer particles at different time.
Thus, the particle flow in the laboratory-scale blast furnace, which was simulated by DEM, correlated with actual flow behavior, and it was confirmed that the parameters used in this simulation work was suitable.

4.2. Analysis of Solid Particle Flow in Blast Furnace Having Bell-type Charging System

Figure 13 shows the snapshots of burden descending behavior in the blast furnace under the rectangular raceway. The gray or dark-gray particles designate coke or iron ore, respectively. The particles descended continuously and additional particle layers were being recharged with time. The particle layers were formed near the side wall, on the other hand, the layers weren’t seen around center of blast furnace, and there were mostly coke. All initial iron ores were melted during about 10 million steps. Figure 14 shows the snapshots of charging behavior of iron ore from 8.17M to 8.29M steps. The collapse of coke layer was observed, and the coke particles were pushed toward the center by compressive force of iron ore, so that, there were mostly coke particles around the center. Another coke particles were also recharged in the bell for upcoming charging process. Figure 15 shows the relation between the stock level and
time step from 7M to 10M steps. The interval of recharging process wasn’t constant, and mean number of steps for its interval was 215,534 steps. This interval corresponds to the actual interval of charging process (around 5 min), thus about 200,000 steps in this calculation might be equal to 5 min in the actual operation. It was found that this simulation model mimicked actual operation. Figure 16 shows the descending velocity fields of particles in the blast furnace at every 30,000 steps from 8.18M to 8.33M steps. The area having high descending velocity runs through the blast furnace from the raceway, and the slip lines are observed between center and side wall. It is found that the velocity field is nonuniform even in both sides. Figure 17 shows the time change of particle descending velocity at 10 spots in the blast furnace; i.e. (a) center and (b) left side, and Fig. 17(c) denotes the schematic diagram of these spots. The particle pulsating flow is observed at the upper spots, and its fluctuation range increases with increasing vertical position. This pulsating flow is quite similar to the case in particle discharge from hopper, i.e. the raceway works as an orifice because the only solid particle flow was analyzed in this simulation. The particles at C3, C4 and C5 don’t move, these spots seem to be in the stagnant zone. The velocities near side wall are much larger than those of center when they are compared at same vertical position. The average cycle of pulsating flow is about 170,000 steps at most of spots, although each phase isn’t same, and this is smaller than the interval of charging process. Figure 18 shows the field of mean descending velocity or horizontal one. The descending velocity increases with increasing the distance from the center, and the velocity near wall is much larger than that of center. It is also large around melting zone, because the iron ore particles are shrinking in there and the porosity of this area increases. The deadman, where the coke particles don’t move, is seen in this figure. The horizontal velocity around the center is nearly zero, thus it is found that these particles descent vertically. On the other hand, the particles near side wall has a little horizontal velocity, and these particles descend along with the side wall. Its velocity is proportional to the distance from the wall. Figure 19 shows the snapshots of descending behavior of charged coke layer. The layer descends in line along with the velocity field, which was shown in Fig. 18. The stagnant zone is also seen in this figure. The charged coke layer reached the raceway for 7.5M steps, and this might be converted to about 3 h according to the adjusting by the interval of charging process (if 200,000 steps = 5 min). Figure 20 shows the mapping of mass of melted ore within 1M steps. Most of iron ore are melting above the raceway, and this area should be the cohesive zone. The adhesion force between particles will be considered for the particles that locate in this area.

The actual operation model of blast furnace having bell-type charging system was proposed in this work. Although only contact force was considered and simplified melting zone or raceway were introduced, this simulation mimicked actual operation very well. This work is the first step of analysis of the blast furnace using DEM, and the followings will be needed in the future work.

i) Adhesion force between particles in cohesive zone
ii) Gas flow from the tuyere
iii) Heat transfer between particles or particle-gas
iv) Melting zone related heat transfer
v) Raceway shape taking into account gas flow condition around tuyere
vi) Considering physical changes of particles
vii) Shrinking rate constant related to chemical reaction

Nevertheless, this large-scale simulation has a high potential to analyze the phenomena found in the blast furnace.

5. Conclusion

The solid particle flow in the blast furnace considering actual operation was modeled by using large-scale DEM. The followings are the summaries of this work.

(1) The particle flow in the laboratory-scale blast furnace, which was simulated by DEM, correlated with actual
Fig. 16. Particle descending velocity fields from 8.00M to 8.33M steps.

Fig. 17. Relation between particle descending velocity and time step.

Fig. 18. Fields of mean velocity in blast furnace.

Fig. 20. Mapping of mass of melted ore.
flow in the experimental work, and it was confirmed that the parameters used in the simulation work was suitable.

(2) The simulation model having bell-type charging system worked very well, and it mimicked the actual blast furnace operation.

(3) The particle pulsating flow was observed at the upper area of blast furnace in this calculation because of no consideration of gas flow. The descending velocity near side wall was much larger than that of center, and the horizontal velocity at the center was nearly zero.

(4) Most of iron ore were melting above the raceway, and the mass of melted ore near the side wall is larger than that of center. This area should be cohesive zone.

(5) This large-scale simulation has a high potential to analyze the phenomena found in the blast furnace, and the abnormal phenomena or serious problem in blast furnace operation will analyzed by considering the adhesion force, gas flow, heat transfer and physical changes in the future.

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REFERENCES


Fig. 19. Snapshots of descending of coke layer.