High-speed Video Recording of Particle Trajectory via Rotating Chute of Nagoya No.3 Blast Furnace and its Comparison with Simulated Behavior Using DEM

Hiroshi MIO,1,* Toshiki NAKAUCHI,2) Yuuki KAWAGUCHI,3) Takashi ENAKA,3) Yoichi NARITA,1) Atsushi INAYOSHI,1) Shinroku MATSUZAKI,1) Takashi ORIMOTO1) and Seiji NOMURA1)

1) Ironmaking R & D Div., Process Research Laboratories, Technical Research & Development Bureau, Nippon Steel & Sumitomo Metals Corporation, 20-1, Shintomi, Futtsu, Chiba, 293-8511 Japan.
2) Ironmaking Technical Dept., Production Div., Hokkai Iron & Coke Corporation 12, Nakamachi, Muroran, Hokkaido, 050-8550 Japan.
3) Ironmaking Div., Nagoya Works, Nippon Steel & Sumitomo Metals Corporation, 5-3, Tokaimachi, Tokai, Aichi, 476-8686 Japan.

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The objective of this paper is to develop a prediction tool for burden distribution of a blast furnace (BF) by using Discrete Element Method (DEM). The high-speed video recording in an actual blast furnace process was tried to capture the particle behavior in Nagoya No.3 BF, and the particle trajectory discharged from a rotating chute was also measured by using a pressure sensitive sheet. The modeling of particle behavior was conducted by DEM, and the simulated behavior was compared with the measured results. The particle discharging behavior was recorded from a large manhole during a shutdown, and an individual particle was able to be seen in the images. It was observed that the particles were pressed up against the chute side wall due to the centrifugal force of chute rotation. The particle discharging velocity was analyzed by Particle Image Velocimetry (PIV). It is found that the velocity of coke particle is larger than that of sinter because of the particle size. This difference affects the particle discharging trajectory, and the one for coke particle is shifted toward the BF wall by comparing to that for sinter. The simulated particle behavior using DEM has a good agreement with the observations, both by the high-speed recording and the trajectory measurement. Therefore, it can be concluded that this particle simulation has high reliability for prediction of the particle trajectory in the actual blast furnace operation.

KEY WORDS: blast furnace; bell-less top; rotating chute; particle trajectory; Discrete Element Method; high-speed video recording.

1. Introduction

A blast furnace is a huge reactor for producing pig-iron from an iron ore, and it has been traditionally used in the world. This is a countercurrent moving bed, and a basic operation is very simple; i.e. the iron ore (sinter, pellet, lumps etc.) and the coke particles are charged into the furnace with alternating layers, and the hot gas is blown from the tuyeres. One of the most important factors for a stable operation is controlling a gas flow in the furnace, because the gas has a key function in the blast furnace for such as a reduction and a heat source. The gas passes through the particle packed bed, thus optimizing packing structure of a burden is an important issue. A great effort has been paid toward the improvement and the estimation of the burden distribution.1–7) Especially, the mathematical model can help the actual daily operation, and it’s widely used at the sites. On the other hand, the information technologies have been developed significantly, and the optical devices for capturing the process have been also developed, i.e. they are Discrete Element Method (DEM)8) and a high-speed video camera. These techniques have a high potential for developing the more precise prediction tool for the burden distribution control. DEM is the one of the most famous and reliable simulation methods for analyzing the solid particle behavior, and many researches using DEM has been already reported.9–16) The particle behavior is basically very complicated, thus the validation of simulated results is the most important issue in DEM work.

In this paper, high-speed video recording in the actual blast furnace process was tried to capture the particle behavior in Nagoya No.3 BF (blast furnace), and the simulated behavior by using DEM was compared with the recorded results. In addition, the particle trajectory discharging from the rotating chute was also measured in Nagoya No.3 BF using a pressure sensitive sheet, and the validation of particle trajectory simulated by DEM was also investigated in detail.
2. Measurement of Particle Trajectory in Nagoya No.3 BF

High-speed video recording was carried out during a shutdown at Nagoya No.3 BF, and the discharging behaviors of coke or sinter particles were recorded. A large manhole was opened, and a high-speed video camera (HiSpec, Fastec Imaging Corp.) and metal halide lamps (HVC-UL 250W, PHOTRON Ltd.) were set around there, as shown in Figs. 1 and 2. The chute was rotated clockwise, and the particle behavior was recorded from side view angle. The chute tilting angle was 51.1 degrees, and the mass flow rates of coke or sinter were 0.11 t/s or 0.67 t/s, respectively. The rotational speed of the chute was 8 rpm. The target of high-speed recording was only first and second rotations because of a cloud of dust. The flame rate of high-speed recording was set 1500 fps, and the particle discharging velocity was analyzed from the recorded images by Particle Image Velocimetry (PIV) using a software (FLOW PIV ver.2.2, library Co., Ltd.). PIV is an image analysis method for measuring 2 dimensional velocities. The velocity filed is analyzed by the difference between two images within a small time step.

The particle trajectory was also measured by using a metering rod. The rod 3.5 m long was inserted into the blast furnace during the shutdown, and Fig. 3 shows the schematic illustration of position relation for the rod and the chute under wall. A pressure sensitive sheet (PRESCALE MW, FUJIFILM Corporation) was put on the rod to get an impact stress. The red patches appeared on the sheet, when the discharged particles impacted on it. The impact stress distribution was analyzed by using a scanner and software (PRESSURE DISTRIBUTION MAPPING SYSTEM for PRESCALE FPD-9270, FUJIFILM Corporation). The main flow position of particle trajectory and its width were obtained. The angle of the inserted rod was 35 degrees against the horizontal direction, and the chute tilting angle was 51.1 and 38.8 degrees. The chute rotational speed and the mass flow rate were same as those for high-speed video recording.

3. Simulation

3.1. Discrete Element Method

Discrete Element Method (DEM) is one of the most popular and reliable simulation methods for the numerical analysis of granular behavior. This simulation method consists of an idea of determining the kinematic force to each finite-sized particle. The main calculation of DEM consists three steps; i.e. 1) particle detection, 2) calculation of forces, 3) update of trajectories, and these processes are looped until $t = t_{\text{max}}$. The contact between two particles is given by Voigt model, which consists of a spring-dashpot and a slider for the friction in the tangential component. The contact forces, $F_n$ and $F_t$, are calculated by following equations.

$$F_{n_{ij}} = K_n \Delta \mathbf{u}_{ij} + \mu_n \frac{\Delta \mathbf{u}_{ij}}{\Delta t} \mathbf{n}_{ij}$$

$$F_{t_{ij}} = C_t \Delta \mathbf{u}_{ij} + \mu_t \frac{\Delta \mathbf{u}_{ij}}{\Delta t} \mathbf{n}_{ij}$$

where $K_n$ is the spring constant, $C_t$ is the damping constant, $\mu_n$ and $\mu_t$ are the normal and tangential friction coefficients, respectively, and $\Delta \mathbf{u}_{ij}$ is the relative velocity between the two particles.

Fig. 1. Picture of setup of high-speed video camera. (Online version in color.)

Fig. 2. Schematic illustration of high-speed video recording.

Fig. 3. Schematic illustration of position relation for the rod and chute under wall.
\[
F_{i,j} = \min \left\{ \mu F_{i,j} | t_j, \left[ K_i \left( \Delta u_{i,j} + \Delta \phi_{i,j} \right) + \eta_i \frac{\Delta u_{i,j} + \Delta \phi_{i,j}}{\Delta t} \right] t_j \right\}
\]

Where, \(K\) and \(\eta\) mean the spring and the damping coefficients. \(\Delta u\) and \(\Delta \phi\) 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. \(m_j\) and \(t_j\) denote the unit vector from \(i\)-th particle to \(j\)-th one in the normal and the tangential components. The subscript \(n\) and \(t\) also denote the normal and the tangential components. The translational and rotational motions of each particle are updated by following equations.

\[
\dot{\mathbf{v}} = \frac{\sum \mathbf{F}}{m} + \mathbf{g} \hspace{1cm} \text{(3)}
\]

\[
\dot{\mathbf{\omega}} = \frac{\sum \mathbf{M}}{I} \hspace{1cm} \text{(4)}
\]

Where, \(\mathbf{v}\) is the vector of a particle velocity, \(\mathbf{F}\) is the contact force acting on a particle, \(m\) and \(\mathbf{g}\) mean the mass of a particle and the gravitational acceleration, \(\mathbf{\omega}\) is the vector of angular velocity, \(\mathbf{M}\) and \(I\) denote the moment caused by the tangential force and the moment of inertia.

The shape of granular material in DEM is usually assumed to be spherical due to the ease of contact detection and calculation of contact force, although that of particles in the blast furnace process is completely irregular. The best solution for considering the particle shape in DEM is to model the exact particle shape. However, it is very difficult because the calculation load becomes extremely large, hence it is not suitable for the simulation of granular flow in the blast furnace process. There are billions and billions of particles in this process. The particle shape affects mainly the flowing behavior and the particle packing construction. The former is more dominant in the case of particle trajectory via rotating chute of blast furnace. Thus, the effect of particle shape on their motion was considered by setting a proper rolling friction, and it is given by Eq. (5).

\[
M_{i,j} = \frac{3}{8} \alpha_i b \left| \mathbf{F}_{i,j} \right| \left| \frac{\omega_i}{\omega_j} \right| \hspace{1cm} \text{(5)}
\]

Where, \(b\) is a radius of contact area, and \(\alpha_i\) denotes the coefficient of rolling friction. Every particle has a different coefficient of rolling friction, because the shapes of particles are totally different from each other. Its distribution is related with the rollability of particle,\(^{11}\) and it is shown in Fig. 4.

| Table 1. Number of calculated particles for coke. |
|-----------------|-----------------|-----------------|
| Particle size [mm] | Number of particles [-] | Mass fraction [-] |
| 25               | 14 405           | 0.15            |
| 40               | 8 675            | 0.37            |
| 55               | 3 878            | 0.43            |
| 75               | 177              | 0.05            |

| Table 2. Number of calculated particles for sinter. |
|-----------------|-----------------|-----------------|
| Particle size [mm] | Number of particles [-] | Mass fraction [-] |
| 10               | 1 017 574        | 0.35            |
| 15               | 254 393          | 0.30            |
| 25               | 50 878           | 0.27            |
| 35               | 5 191            | 0.08            |

Fig. 4. Distribution of coefficient of rolling friction.

Fig. 5. Recorded images of charging coke particles by high-speed video camera.

Fig. 6. Recorded images of charging sinter particles by high-speed video camera.
The method having individual rolling friction had given the significant agreement with the experimental results,\(^{11}\) therefore this method was applied to the present work.

### 3.2. Simulation Conditions

The particle behavior during charging process of rotating chute was simulated by DEM, and the discharging velocity and the particle trajectory were compared with measured results in Nagoya No.3 BF. The particles were generated under the conditions of 0.11 t/s (coke) or 0.67 t/s (sinter) at the chute hanging point, and they had a proper vertical velocity, which was related to the free-fall from the hopper gate. The particles were fallen on the rotating chute, slid and

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**Fig. 7.** Particle discharging velocity field analyzed by PIV.

**Fig. 8.** Snapshots of particle discharging behavior simulated by DEM.

**Fig. 10.** Picture of pressure sensitive sheet after the impact of sinter particles.

**Fig. 13.** Snapshots of particle trajectory simulated by DEM.
discharged from the chute. The simulation areas for a circumferential direction and a vertical one were 360 degrees and 7 m below from the chute hanging point, respectively. The rotational speed of the chute was 8 rpm. The particle behavior was simulated during one rotation, thus the total mass of calculated particles were 0.825 t (coke) or 5.0 t (sinter), respectively. The particle densities were 1 050 kg/m³ (coke) or 3 300 kg/m³ (sinter), and the ranges of particle size were 25–75 mm (coke) or 10–35 mm (sinter). The small sizes of sinter particles were cut to reduce the computation load. The detailed particle conditions were tabulated in Tables 1 and 2. The coefficient of rolling friction for each particle was set by generating a random number at the beginning of the simulation, and their distribution corresponded to Fig. 4.

4. Results and Discussions

4.1. Discharging Behavior

Figures 5 and 6 show the images recorded by high-speed video camera during charging into the blast furnace under the condition of 51.1 degrees in chute tilting angle. The high-speed recording was completed during first rotation, and the individual particles could be seen in the images. However it was difficult to see the particles during second rotation due to the dust. The particles were pressed up against the chute side wall caused by the centrifugal force of chute rotation, and this behavior is mostly same in both cases; i.e. coke charge and sinter one. Figure 7 shows the particle discharging velocity fields, which were analyzed by PIV. The portion of image seems to be a whiteout because of a halation; however, there is enough area for the velocity analysis. The average discharging velocities were obtained at just after the outlet, and they are given as follows; coke: 5.23 m/s and sinter: 4.75 m/s. It is found that the discharging velocity of coke particle is larger than that of sinter. The roughness of chute inner surface affects the sinter particles more than coke because of their size, thus the velocity of sinter particle is smaller than that of coke.

Figure 8 shows the snapshots of particle discharging behavior at 51.1 degrees of chute tilting angle, which were simulated by DEM. The particle behaviors are quite similar to the images which were recorded by the high-speed video camera, as shown in Figs. 5 and 6. The particle velocity at the outlet of rotating chute was also analyzed in DEM. Although each particle had three dimensional velocities, the one for rotating direction (circumferential direction) was not taken into account in the discharging velocity analysis, because this direction couldn't be captured by PIV using high-speed video images. Figure 9 shows the distributions of particle discharging velocity during one rotation. The distribution for coke particle is very narrow, on the other hand, that for sinter seems to be wider and shifted toward the smaller range, because the movement of smaller particles is affected by the roughness of chute wall. The average velocities are calculated; i.e. coke: 5.10 m/s and sinter: 4.69 m/s, respectively. These values and tendencies are quite similar to the measurement results in Nagoya No.3 BF, therefore the particle behavior simulated by DEM has a good correlation with the observed results.

4.2. Particle Trajectory

Figure 10 shows an example of picture of the pressure sensitive sheet after the impact of sinter particles, and red patches can be seen on the sheet. The impact stress distribution was analyzed by using the scanner and software, and the impact force was calculated from it. The impact force for width direction of the rod was summed, and the one for longer direction was evaluated as 0.5 mm of a grid size. Figures 11 and 12 show the impact force distributions.
Table 3. Main flow position of particle trajectory from the rod tip.

| Chute tilting angle [deg] | 51.1 | 38.8 |
|--------------------------|------|------|
| Coke                     | 1,981 mm | 887 mm |
| Sinter                   | 1,974 mm | 831 mm |

Fig. 12. Impact force distribution for sinter charging.

Fig. 14. Comparison of the impact force distribution and the passing particle mass distribution for coke charging.

Fig. 13 shows the snapshots of particle trajectory simulated by DEM, the main flow positions, which were measured in Nagoya No.3 BF, are also drawn in these figures. The simulated trajectories correlate highly with the measured data, regardless of particles and chute angles. The mass of passing particles at the metering rod position was calculated to compare the particle trajectory in detail. Figures 14 and 15 show the comparison of the impact force distribution (measured) and the passing particle mass distribution (DEM). The tendencies of the distribution are quite similar, however the width of measured results is larger than that of simulation. The particle movement in the actual condition is influenced by many factors; such as joint of chute lining, chute wear, particle shape and so on, thus the particle flow becomes wider, whereas the behavior of the simulation is smart. Therefore these differences are reasonable and proper. As describe above, it can be concluded that the particle simulation developed by using DEM has high reliability for prediction of the particle trajectory in the actual blast furnace operation.

5. Conclusions

In this paper, high-speed video recording was carried out in Nagoya No.3 blast furnace to observe the actual particle behavior, and the particle trajectory discharged from the rotating chute was measured. The modeling of particle behavior was also conducted by the numerical analysis using Discrete Element Method, and the simulated behavior was compared with the observations. The followings are summaries of this work.
(1) The particle discharging behavior was recorded from the large manhole during a shutdown, and the individual particle can be seen in the images. It was observed that the particles were pressed up against the chute side wall due to the centrifugal force of chute rotation.

(2) The particle discharging velocity was analyzed by PIV. It is found that the velocity of coke particle is larger than that of sinter because of the particle size. This difference affects the particle discharging trajectory, and the one for coke particle is shifted toward the BF wall by comparing to that for sinter.

(3) The simulated particle behavior using DEM agreed with the observations, both by the high-speed recording and the trajectory measurement. Therefore, it can be concluded that this particle simulation has high reliability for prediction of the particle trajectory in the actual blast furnace operation.

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