1. Introduction

In the ironmaking process, pulverized coal has been injected into the blast furnace as an alternative reducing agent of coke since the 1980s. In recent years, the proportion of pulverized coal injection (PCI) in the reducing agent tends to increase with the increase in worldwide production of iron. Coal prices exceeded 150 USD/t in 2010 and continue to fluctuate widely. Therefore, shifting from coking coal to cheaper reducing agents is desired. Moreover, from the viewpoint of CO₂ mitigation, the injection rate of reducing agents such as pulverized coal (PC) or H₂ from a tuyere will be increased with increasing coefficients of friction and resistance. Moreover, the impact of the flow velocity of the gaseous phase on the accumulation behavior of powder was examined. The frictional force on powder particles at the bottleneck increased with an increase in the gas velocity. The clogging of powder occurred easily as a result.

KEY WORDS: blast furnace; ironmaking; powder; packed bed; numerical simulation; DEM; accumulation; permeability.

Owing to powder accumulation in the packed bed, the permeability of gas and liquid deteriorates, which decrease throughput of the blast furnace. Powder in the moving bed has a large effect on the productivity and efficiency of the blast furnace process when operating with low coke rate and using high-reactivity coke. Therefore, an investigation on the effect of the powder's physical properties and the moving bed material on transport phenomena and the accumulation mechanism of powder in the blast furnace is essential.

In the present study, the motion of powder particles was simulated using the discrete element method (DEM), and the effect of the powder particles' shape on the behavior and accumulation of powder was investigated. The study used DEM to reproduce the movement of particles by solving the equations of motion of individual particles. Since the particles were treated as spherical objects in DEM, contact friction and rolling resistance were implemented to represent the irregular shape of actual powder particles. The calculation results showed that contact friction and rotational resistance affected the static holdup of the powder. The amount of clogging of powder at a bottleneck in the moving bed increased with increasing coefficients of friction and resistance. Moreover, the impact of the flow velocity of the gaseous phase on the accumulation behavior of powder was examined. The frictional force on powder particles at the bottleneck increased with an increase in the gas velocity. The clogging of powder occurred easily as a result.

KEY WORDS: blast furnace; ironmaking; powder; packed bed; numerical simulation; DEM; accumulation; permeability.

Analysis of Powder Motion in a Packed Bed of Blast Furnace Using the Discrete Element Method

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et al.\textsuperscript{13} analyzed the movement of powder in a packed bed and showed the clogging phenomenon of powder in the vacancy between packed material using particle simulation by the discrete element method and computational fluid dynamics (DEM-CFD). In the present study, by considering the behavior of powder in a coke-moving bed at the lower part of the blast furnace, powder flow in the packed bed was simulated by DEM. The powder motion derived by DEM was evaluated by comparing it with actual powder motion in experiments. Furthermore, by utilizing the characteristics of DEM, the behavior of the powder was calculated by changing the physical properties of the particles and the effects of particle properties on the accumulation behavior in the packed bed were studied.

2. Representation of the Powder by DEM

2.1. Fundamental Equation of DEM

DEM is used to study the motion and effect of a large number of particles such as motion analysis of non-continuous solid flows, as it is possible to track the particle behavior independently. Because it has been discussed in detail in previous papers.\textsuperscript{11,12} An outline of the DEM configuration is provided here. The contact force in the DEM particle system is shown in Eq. (1). Owing to the stress and moment from the particle–wall and particle–particle contact points among the DEM particles, rotational and translational motions are determined. The contact force is calculated by the Voigt model that is approximated by a spring, dashpot, and friction slider. The friction slider is implemented to account for slipping at a contact point. The translational displacement $u_i$ of the $i$th particle by forces acting on it is expressed as follows:

$$m \frac{d^2 u_i}{dt^2} + \eta \frac{du_i}{dt} + Ku_i + m_i g = 0 \quad \text{(1)}$$

and the rotational displacement $\omega_i$ is determined by

$$I_i \frac{d^2 \omega_i}{dt^2} + \eta R_i^2 \frac{d\omega_i}{dt} + K R_i^2 \omega_i = 0 \quad \text{(2)}$$

where $m$, $R$ and $I$ represent the mass, radius and moment of inertia of the $i$th particle, respectively. $K$ and $\eta$ denote the spring constant and the viscosity coefficient of the dashpot, respectively. There are generally a large number of particle contacts around one particle, so Eqs. (1) and (2) must be satisfied at all contact points. This calculation is repeated in specific time increments, and each element is tracked sequentially.

The time step was set to $10^{-6}$ s for the powder and $10^{-5}$ s for the packed bed particles, and the trajectory of motion of the particles was calculated. The interparticle contact force was determined by the Voigt model, and the coefficients used were determined based on the physical properties of the particles. The particle considered in the DEM model was spherical. In order to represent the shape accurately, rolling friction was added. The original rolling friction represents the energy dissipation mechanism with elastic deformation at the contact point.\textsuperscript{13} $M_i$ is defined as a function of rolling friction coefficient such that

$$M_i = \frac{3}{8} \alpha b |f_r| \quad \text{(3)}$$

where, $\alpha$, $b$ and $f_r$ are the rolling friction coefficient, radius of contact circle and normal stress, respectively. In order to represent the irregular shape of coke, the rolling friction used in the present study might be different from the value for the original rolling friction.

2.2. Relationship between Rolling Friction Coefficient and Angle of Repose

In present study, the irregular shape of the powder particles was represented using the rolling friction. The rotational resistance coefficient was determined from the relationship between the rotational resistance of a particle and the angle of repose. It was calculated by piling particles with arbitrary rotating resistance coefficients on a dish. The physical properties of alumina powder with a diameter of 0.5 mm was used for a powder particle. A shallow cylindrical container with a diameter of 50 mm was selected for the calculations, and a total number of 3 550 powder particles were set to free-fall from the center of the container. The calculation was continued until a steady state was reached, and the angle of repose was measured. Using this method, the effect of the rolling friction coefficient on the angle of repose was derived. The result is shown in Fig. 1, where the solid, dashed and chain lines represent the calculation result with contact friction coefficients of 0.1, 0.5 and 0.7, respectively. The angle of repose increased with increasing rolling friction coefficient. However, when the rolling friction coefficient was over 10, the repose angle became almost constant. When the friction coefficient was small, the effect of the rotational resistance on the angle of repose was small.

3. Experiment of Powder Flow in Packed Bed

The validity of DEM were assessed for reproducing the powder flow in the moving bed of a blast furnace by comparing the powder flow in a packed bed obtained in experiments with the cold model and simulation using DEM.

3.1. Experimental Apparatus and Specimen

An experimental apparatus in which powder could be charged onto a packed bed of alumina balls was constructed. A schematic of the experimental apparatus is shown in Fig. 2. A tube of 90 mm in inner diameter was filled randomly with alumina balls of 10 mm in diameter, and the packed

![Fig. 1. Influence of rolling friction on the repose angle of powder particle.](image)

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bed was filled to a height of about 100 mm. To support the packed bed, a mesh was installed at the bottom of an acrylic tube. The mesh was made of stainless steel wire of \(0.5\) mm with \(3.6\) mesh. A glass funnel measuring \(90\) mm in diameter, with a stem length of \(55\) mm and inner stem diameter of \(7\) mm, was placed over the packed bed. A plastic tube with an inner diameter of \(8\) mm and a length of \(72\) mm was connected to the funnel stem. The distance between the bottom of the plastic tube and the top of the packed bed was \(10\) mm. Alumina particles with a diameter of \(0.5\) mm were used as powder particles. Initially, the end of the plastic tube was closed and \(30.0\) g of alumina powder was placed in the funnel.

### 3.2. Experimental Procedure

The end of the plastic tube was opened, and the powder particles descended onto the packed bed at a flow rate of \(15\) g/s. The relationship between the number of particles that passed and the distance from the center of the packed bed was measured at the collection plate. The experimental conditions are shown in Table 1.

A flat board on which the powder (alumina powder) adhered uniformly and a board on which packed-bed particles (alumina balls) adhered uniformly were prepared. The board adhered with packed-bed particles was placed on the board with adhered powder, and the boards were tilted gradually. The measured angle at which a board began to slide was \(25^\circ\). The relationship between the angle \(\theta\) and the contact friction coefficient, \(\mu\) is expressed as follows:

\[
\mu = \tan \theta \quad \text{................................. (4)}
\]

When \(10\) g of powder was dropped on the board, the angle of repose measured was \(23.8^\circ\).

### 3.3. Calculation Conditions of DEM

The parameter used in the simulation is shown in Table 2. First, the packed bed structure was generated by DEM. As shown in Fig. 3, particles with a diameter of \(10\) mm were dropped into a cylinder measuring \(100\) mm in diameter and \(100\) mm in height, and the packed bed structure was formed. The rotational resistance coefficient was determined as \(0.1\), based on Fig. 1, for which the angle of repose was \(24^\circ\) with \(\mu=0.5\). A funnel-shaped wall was installed over the packed bed as in the experiment, and the powder was deposited onto the packed bed from the funnel. The powder motion was then calculated. At the bottom of the packed bed, the number of particles that passed was counted and the diffusion from the center was obtained.

### 3.4. Verification of the Calculation Result

The dispersion of the particles that passed the packed bed was measured experimentally and by simulation. Figure 4 shows a comparison of the results. Since a concentric collection plate was used, the collection area differed for each
collection radius. Therefore, the collection ratio was normalized by the following:

\[
\text{Collection ratio} = \frac{\text{Amount of powder for a collection site} / \text{area for a collection site}}{\text{Total amount of powder} / \text{Total area of collection site}}
\]

(5)

The powder supplied to the center of the packed bed made contact with the packed-bed particles repeatedly and diffused in a radial direction. The results of the experiment and the simulation agreed well with each other for every collection radius. With control of the physical properties of the particles in the calculation, the motion of the powder in a packed bed was reproducible using DEM.

4. Effect of a Wall on Powder Flow in a Packed Bed

The particles would be aligned along the wall, and thus the vacancy is increased in the vicinity of the wall. Flow of gas and powder tends to concentrate near the wall, therefore the evaluation of the gas flow and powder in packed bed is difficult. Tsuji et al. reported the impact of a flat wall on the vacancy of a packed bed. Here, the influence of a cylindrical wall on the packed bed structure and powder flow was investigated using DEM.

4.1. Calculation Conditions

In order to estimate the effect of vacancy near the wall on the powder flow, the distribution of the particles that passed the packed bed was measured by the same method mentioned above. The condition and physical properties of the packed bed and powder assumed for the calculation were the same as those described in section 3.3. However, to prevent clogging in the analysis of powder flow, the contact friction and rotating resistance were set to zero. A total of 54 745 powder particles were uniformly dropped from the upper surface of the packed bed. In one case, a cylindrical wall (Φ 90 mm), which affected only the powder particles, was installed inside the packed bed. The distance of the wall from the wall surrounding the packed bed was 5 mm.

4.2. Wall Effect on Powder Flow

The effects of the cylindrical wall and inner wall on the powder flow and distribution though the packed bed are shown in Fig. 5. The solid and open circles, and the broken line denote the distribution of particles passed the packed bed with and without the inner wall, and void fraction of the packed bed, respectively. The void fraction near the wall (at 50 mm in the horizontal axis) was the highest, and it fluctuated with the variation in diameter of the packed material. The fluctuation decreased gradually and was observed over a range that was about three times the diameter of a packed particle (20 mm in the horizontal axis), which agreed with the reported result. When the inside wall was not considered in the calculation, as shown by the gray line, the powder flow concentrated near the area where the wall would have been located and exhibited the minimum value at a distance of 1 packed-bed particle radius from the wall. The fluctuation in the number of passing particles was observed over the range of about three times the particle diameter. On the other hand, when the inner wall was installed, the number of powder particles that passed was almost uniform.

A schematic sketch of the powder particle motion near the wall is shown in Fig. 6. The domain within a distance equivalent to the particle radius from the surface of the wall is shown as shaded area in Fig. 6, the void fraction was higher and the contact frequency of a powder particle with the packed-bed particles was lower than that of center region. The frequency of a powder particle leaving this domain was low.
In this region, a powder particle contacting with the packed-bed particle easily moves towards the wall, and the frequency of the powder particle moving towards the center would decrease. The probability of a powder particle that had entered the shaded region in Fig. 6 subsequently leaving the region was low, and thus, the powder flow was concentrated near the wall. If the inner wall was installed, concentration of powder particles near the wall was mitigated, and uniform particle flow was achieved.

5. Influence of Physical Property of Powder on the Flow in Packed Bed

5.1. Calculation Condition

The contact friction coefficient and rotational resistance coefficient of the powder particle in the packed bed were changed arbitrarily for this calculation; the other conditions were the same as shown in Table 2. In order to avoid the influence of the wall on the powder flow, an inner wall (Φ 90 mm), as discussed above, was installed. Here, in order to investigate the influence of gas flow, the drag force on a powder particle was given, assuming that there was perpendicularly uniform gas flow towards a packed bed. A standard gas flow with a superficial velocity of 1.75 m/s was used, and its drag force on particles is given by the following equations depending on the Reynolds number Re:

\[ F = C_D \frac{\pi d^2}{4} \cdot \frac{1}{2} \rho u^2 \] .......................... (6)

where \( C_D, d, \rho, \) and \( u \) denote the drag force coefficient, diameter of a powder particle, density of the gas phase, and relative velocity of the gas and powder, respectively. The density of the gas phase was 1.2 kg/m³. A powder particle flowed from a position that was 10 mm below from the bottom of the bed into the entire packed bed uniformly in horizontal direction, passing through the inside of the packed bed, and was discharged by the gas flow from the top of the packed bed. Immediately after that, 6,221 powder particles were injected at intervals of 0.1 s; a total of 124,420 powder particles were injected after the process was repeated 20 times. In order to investigate the influence of the friction coefficient and the rotational resistance coefficient, their values were changed and the calculation results were compared. The friction and rotational resistances represent texture and shape of powder particle.15)

5.2. Influence of Physical Property on Behavior of Powder

Figure 7 shows the dispersion of powder flow for two conditions. The friction coefficient and the rotational resistance coefficient are (i) 0.0 and 0.0, and (ii) 0.9 and 9.0,

\[ C_D = \frac{24}{Re} \quad (Re < 5.67) \] .......................... (7)

\[ C_D = \frac{10}{\sqrt{Re}} \quad (5.67 < Re < 516.53) \] .......................... (8)

\[ C_D = 0.44 \quad (516.53 \leq Re) \] .......................... (9)

where \( C_D, d, \rho, \) and \( u \) denote the drag force coefficient, diameter of a powder particle, density of the gas phase, and relative velocity of the gas and powder, respectively. The density of the gas phase was 1.2 kg/m³. A powder particle flowed from a position that was 10 mm below from the bottom of the bed into the entire packed bed uniformly in horizontal direction, passing through the inside of the packed bed, and was discharged by the gas flow from the top of the packed bed. Immediately after that, 6,221 powder particles were injected at intervals of 0.1 s; a total of 124,420 powder particles were injected after the process was repeated 20 times. In order to investigate the influence of the friction coefficient and the rotational resistance coefficient, their values were changed and the calculation results were compared. The friction and rotational resistances represent texture and shape of powder particle.15)

![Fig. 7. Influence of physical parameter on distribution of powder particle.](image-url)
respectively. The left figure shows general view, and the right figure shows the vicinity of packed particle. The dots in the figure denote powder particles, and the packed-bed particles are not shown. At \( t=0 \) s, the powder resided at the bottom uniformly. At \( t=0.2 \) s, the particles supplied earlier were moving up in the packed bed. The velocity of the powder in case (i) was higher than that in case (ii), and the amount of time spent in the packed bed was shorter in case (i). At \( t=0.2-0.3 \) s, the powder began to reach the top of the packed bed, and the flow rate of particles at the outlet became constant by \( t=0.4-1.5 \) s. After reaching a stationary state, the supply of the powder was stopped at \( t=2.0 \) s.

The powder particles that remained in the packed bed were continuously discharged at \( t=2.5-4.0 \) s; the number of particles in the packed bed decreased and became constant. At \( t=5.0 \), sufficient time had passed after the powder supply was stopped. No accumulation was observed in case (i), and all the powder particles were discharged from the packed bed.

In case (ii), the powder clogged the bottleneck where the local packing density was high, and accumulated particles were observed on the clogging.

After the calculation began, the number of powder particles in the packed bed increased and reached a steady value with a constant supply of powder particles. A dynamic holdup is defined as the difference between the number of the powder particles in the packed bed at the steady state, which occurred at \( t=5.0 \) s. A static holdup is defined as the difference between the number of supplied and discharged particles.

The influence of the physical properties of particles on the holdups is shown in Fig. 8. The solid and broken lines denote the dynamic and static holdups, respectively. The holdup ratio is defined as the volume of powder divided by the volume of vacancy in the packed bed, as follows:

\[
\text{Hold up ratio} = \frac{\text{volume of powder particle} \times \text{number of powder particle}}{\text{volume of vacancy in the packed bed}}
\]

When the rotational resistance coefficient was 9.0 and the contact friction coefficient was over 0.3, since it had not been in a static state at \( t=2.0 \) s when the powder supply ended, a dynamic holdup could not be derived. Dynamic holdup increased with increasing friction coefficient. Moreover, when a friction coefficient was 0.3 or higher, dynamic holdup increased with increasing rotational resistance coefficient, but when a friction coefficient was small, the increase in dynamic holdup was small.

Subsequently, static holdup is considered. As seen for dynamic holdup, static holdup increased with increasing friction coefficient and rotational resistance coefficient. However, when the rotational resistance coefficient was small, the influence of variation in friction on the static holdup was small. Moreover, when the friction coefficient was near zero, static holdup had not been observed. Therefore, the accumulation mechanism can be explained as follows. Figure 9 represents the mechanism of the static holdup caused by friction. The powder particles that went up the inside of the packed bed via gas flow formed the first accumulation layer in a bottleneck caused by friction between the powder and packed-bed particles, shown as striped particles in Fig. 9. The powder then accumulated on the first clogged layer at the bottleneck. The maximum amount of accumulation was determined by the rotational resistance of the particles. Therefore, since the first accumulation particle layer was not formed when the friction coefficient was small, and the packed-bed particle was large enough compared to the powder, there was no clogging or accumulation.

Cracking by burden degradation, powdering of iron ores with reduction, and unburned char all increase the amount of powder in a blast furnace. The powder generated by wear of materials is irregular in form, and its rotational resistance and friction coefficient might be large. The shape of unburned char is comparatively smooth, and its rotational resistance coefficient and friction coefficient are small. The
motion of the powder in a packed bed may be dependent on the source of powder generation.

5.3. Influence of Gas Flow Rate on Accumulation of Powder

The influence of the gas flow rate in a packed bed on the accumulation of powder was investigated. The values of 0.3 and 0.9 for the rotational resistance coefficient and the values of 3.0 and 9.0 for the friction coefficient were chosen as the physical properties. The gas flow rate was 1.09, 1.3, 1.74 or 2.17 m/s in superficial velocity.

Figure 10 shows the powder particle dispersion with a friction coefficient of 0.3 and a rotational resistance of 9.0. Cases (iii) and (iv) represent gas velocities of 1.09 and 2.17 m/s, respectively. As shown in case (iii), the average velocity of a powder particle was small, and the holding time in the packed bed became long.

The difference in this average velocity appeared in the response time of the output at the top of the packed bed. Under the condition shown in case (iii), the discharge of powder particles from the packed bed began at about $t=0.7$ s, and the particle dispersion reached a static state at $t=1.8$ s. Under the condition shown in case (iv), discharging started at $t=0.1$, and a static state was reached at $t=0.7$ s. After the powder supply was stopped at $t=2.0$ s, the discharge of particles continued until $t=4.0$ s, as shown in case (iii). However, particles were no longer discharged at about $t=2.5$ s, as shown in case (iv). Static holdup was observed at $t=5.0$ s, where the amount of holdup shown in case (iv) was higher than that shown in case (iii).

The influence of gas velocity on holdup is shown in Fig. 11. The dynamic holdup increased with decreasing gas flow rate. On the other hand, static holdup increased with increasing gas flow rate. These results did not agree with an earlier experimental result in which static holdup increased with decreasing gas velocity. A schematic sketch of the accumulation of powder at the bottleneck is shown in Fig. 12. When the gas flow rate is high, the gas drag force on the powder...
powder particle is large. Powder is concentrated and pushed at the bottleneck, which makes clogging easy to occur at a high flow rate. When the gas flow rate is low, the pressure on particles is also low and the influence of friction becomes small, which means clogging does not form easily. In an experiment reported in the literature,\textsuperscript{16)} since very fine powder was used, the clogging did not occur at a bottleneck easily, and accumulation by this mechanism did not happen. These results show that it is necessary to examine the dependence of the accumulation mechanism on particle diameter in further studies.

6. Conclusions

A numerical simulator of powder motion in a packed bed was designed using DEM. The effects of the shape of powder particles and the friction between them on their accumulation in the packed bed were analyzed. The following conclusions were obtained:

(1) Comparisons of the calculation results with the experimental results showed that by appropriately selecting the physical properties of the particles, the powder motion can be obtained with high accuracy by DEM.

(2) The formation of the first accumulation layer at the bottleneck of a packed bed depends on the contact friction between the particles, while the amount of accumulation is determined by the shape of the particles.

(3) Dynamic holdup increases with decreasing gas flow rate. On the other hand, static holdup increases with increasing gas flow rate.

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