Numerical Simulation of Particle Agglomeration and Bed Shrink in Sintering Process

Toshihiko UMEKAGE1) and Shinichi YUU2)

1) Graduate School of Engineering, Department of Mechanical and Control Engineering, Kyushu Institute of Technology, 1-1 Sensui-cho, Tobata-ku, Kitakyushu 804-8550 Japan. 2) Ootake R and D Consulting Office, 1-17-27-508 Ootake, Higashi-ku, Fukuoka 811-0322 Japan.

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The motions of the particles and the gas in the actual scale sintering bed were simulated to elucidate the mechanism of the bed structure changes, the bed shrink and the local void formations by the simultaneous calculation of Navier–Stokes equations and the Lagrangian DEM equations based on the simple sintering model in which the phase change of particles and the cohesion forces due to the liquid bridges among particles were considered.

The bed shrink rate decreased with the moving downward of the melting zone. This is mainly because the weight of the particle bed increases with increasing the bed height. The gap of the particle motions occurred between the zones of which the content and the contact number were largely different. The gap separates contact particles and the crack appears. The shrinks of the beds with the large particles (MEBIOS particle) were smaller than that of the bed without the large particles. The reasons are that the large particles do not change the particle volume and also the high void region around the large particles is formed. The crack did not occur in the particle bed placing the large particles. The large scale zones of which the content and the contact number are largely different are cut off by the large particles and the small crack originated from the separation of contact points between iron ore particles does not grow by the existence of the large particles. After the sintering the high number density areas on the large particles and the void areas under the large particles were formed. This is because the large particles with smaller particle density relatively ascend among the small particles with the larger particle density. The void areas under the large particles advance the aggregation among the small particles which do not contact with the large particles.

KEY WORDS: sintering process; sintering bed; numerical simulation; distinct element method; finite difference method; Navier–Stokes equation; cohesion force; large particle; liquid film.

1. Introduction

Numerical simulation of particle bed is one of the most interesting research topics in sintering process. Ramos et al.1) developed the numerical simulation model to describe the structural change in the iron ore sintering bed. They used Distinct Element Method (DEM)2) and did not consider the motion of gas flows. They calculated the structure changes in the small scale model bed. The results show that the carbon content and the melting temperature affect the final structure of the bed. Yamaoka and Kawaguchi3) developed 3-dimensional mathematical model for the sintering process to make an optimize design of sintering process. The pot test shows that the model could calculate the transitions of gas temperature and compositions, and the distributions of pore ratio and mineral compositions inside the sintering cake. Aizawa and Suwa4) proposed the artificial unit-cell model based on Phase Field Model and Finite Element Method. The results show that the model would be a reliable tool to control the size, shape and distribution of mesopores.

In this study the particle and the gas motions in the actual scale sintering bed have been presented to elucidate the mechanism of the bed structure changes, the bed shrink and the local void formations. Navier–Stokes equations for the gas and Lagrangian equations of particle motion have been simultaneously solved numerically. The many body interactions among particles in the bed have been calculated using DEM.2) The cohesion force which acts on the contact particles with the melting liquid film have been calculated using the liquid bridge force and the drag force which acts on approaching particles with the liquid film have been considered. The simulation has been performed in the actual scale bed of which height was about 600 mm to predict the large scale bed structure change. The structure changes in the sintering beds of the small particles of which diameters were less than 3.9 mm and in the sintering bed placing the large particles (MEBIOS particles) have been simulated.

2. Computational Procedure

2.1. Gas Phase Calculation

The governing equations for the gas phase are the 3-dimensional Navier–Stokes equations for the incompressible
fluid with interaction terms between the gas and particles, and the fluid continuity equation. In the present simulation the air was used for the gas. The non-dimensional forms are as follows:

\[ \varepsilon \frac{\partial \mathbf{u}}{\partial t} + \varepsilon (\mathbf{u} \cdot \nabla \mathbf{u}) = -\varepsilon \nabla p + \frac{\varepsilon}{Re} \left[ \nabla^2 \mathbf{u} + \frac{1}{3} \nabla (\nabla \cdot \mathbf{u}) \right] \]

\[-St - St_L \] ...............(1)

\[ \frac{\partial \varepsilon}{\partial t} + \varepsilon \nabla \cdot \mathbf{u} = 0 \] ...............(2)

St and St_L in the above equations are the interaction terms of the drag and the lift forces between the gas and particles. Motions of the gas and particles linked through these interaction terms. Substitution of the drag coefficient into the equation of the drag force gives the equation for St. We used Schiller and Naumann's experimental drag coefficient, which is applicable to flows of the particle Reynolds number Re_p < 1000.

\[ St = \frac{3 \pi D_p N D (1 + 0.15 Re_p^{0.687})}{U_p \rho} (u - u_p) \xi(\varepsilon) \]

\[(0 \leq Re_p \leq 1000) \] ...............(3)

When Re_p is larger than 1000, Newton's drag coefficient gives the following equation.

\[ St = 0.055 \pi D_p^2 N D (u - u_p)^2 \xi(\varepsilon) \quad (1000 < Re_p) \] ...............(4)

The correction factor \( \xi(\varepsilon) \) in the above equations describe the effect of neighboring particles on the drag force. We used the experimental equation presented by Umekage and Yuu.\(^6\)

\[ \xi(\varepsilon) = 3.8 - \frac{5.4}{\varepsilon} + \frac{2.6}{\varepsilon^2} \] ...............(5)

For the lift force term St_L, we used the following equations.

\[ St_L = \frac{C_L}{16} \left( \frac{D_p}{\Omega^*} \right)^3 N (u - u_p) \times \left( \frac{1}{2} \nabla \times u - \omega_p \right) \xi(\varepsilon) \]

.........................(6)

We used Eq. (7) obtained by formulating Kurose and Komoriso's\(^3\) calculated data for the lift coefficient C_L.

\[ C_L = \frac{2 \Omega^*}{21 \pi Re_p^{0.7}} \] \( (0 \leq Re_p \leq 10) \)

\[ C_L = 0.1995 \Omega^*^{0.809} Re_p^{0.274} \] \( (10 \leq Re_p \leq 200) \) \( \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots
ore particles, the limestone particles and the coke particles were 85%, 10% and 5% respectively and the motions of 78,000 particles were calculated. Figure 2 shows the particle size segregations which are nearly equal to the measured values in the actual furnace. The particle size at the arbitrary location in each column in Fig. 2 was calculated by the linear proportion method. The solid boundary condition for the particles and the outflow boundary condition with the constant velocity $U_0/\Delta H = 0.68$ m/s for the sucking gas at the bottom of the bed were used. $U_0/\Delta H = 0.68$ m/s is the real sucking gas velocity measured at the bottom of the actual sintering bed. The free inflow boundary condition were used for the gas at the top $(Z = 2,880$ mm) of the computational domain in order to be able to calculate the flow field for the sufficient long period.

2.4. Movement of Melting Zone and Phase Change of Particles in Melting Zone

2.4.1. Movement of Melting Zone

The model that the vertical width of the melting zone changes from 25 mm at the top of the particle bed to 75 mm at the bottom represents the growth of the melting zone with approaching to the bottom of the particle bed according to the combustion. It means that the descending velocity of the melting zone at the top of the bed set to be smaller than that at the bottom of the bed as shown in Fig. 3. The descending velocity of the melting zone in the present simulation was set to be about 100 times larger than that of the actual sintering process in order to represent the sintering process by the simulation in which the calculation for the long time as the actual sintering process takes place is extremely difficult.

2.4.2. Model of Particle Phase Change in Melting Zone

- [Iron ore particles of which content is 85% number based of whole particles]

When the bottom of the melting zone reached an iron ore particle center, 50% of the particle volume melted and the diameter $D_p$ of the ore particle reduced to $0.794D_p$ by melting the particle surface. The cohesion force by Eq. (15) acted between the particles contacted by the melting liquid and the drag force by Eq. (16) acted on the particle by the melting liquid around the particle surface. In this model $0.794D_p$ was used for the particle diameter in DEM calculation in the melting zone and $1.0D_p$ was used in the calculation of the interaction force between gas and particle, and the packing fraction, whichever the particle surface was the solid of the ore or the melted liquid. When the top of the melting zone reached the particle center, the angular velocity set to be zero, the cohesive force between contact particles was taken to become 10 times larger than the cohesion force by melting liquid and the friction coefficient was also taken to become larger to be 1.0 from 0.45. These represented the fixation of the particles after the sintering process.

- [Limestone particles of which content 10% number based of whole particles]

When the bottom of the melting zone reached a limestone particle center, 45% of the particle volume was gasified and the remaining 55% of the particle volume converted to the solid phase. The cohesion force by Eq. (15) acted between the particles contacted by the gasification liquid and the drag force by Eq. (16) acted on the particle by the gasification liquid around the particle surface. In this model $0.794D_p$ was used for the particle diameter in DEM calculation in the melting zone and $1.0D_p$ was used in the calculation of the interaction force between gas and particle, and the packing fraction, whichever the particle surface was the solid of the or the gasified liquid. When the top of the melting zone reached the particle center, the angular velocity set to be zero, the cohesive force between contact particles was taken to become 10 times larger than the cohesion force by gasification liquid and the friction coefficient was also taken to become larger to be 1.0 from 0.45. These represented the fixation of the particles after the sintering process.

![Fig. 1. Computational domain.](image)

Table 1. Computational conditions.

| Computational cell sizes | $\Delta X \times \Delta Y \times \Delta Z$ |
|--------------------------|----------------------------------|
| Superficial suction gas velocity, $U_0$ | 0.68 m/s |
| Time step, $\Delta T$ | 5.0 $\times 10^{-4}$ s |
| Number of particles | |
| Iron ore | 66,300 |
| Coke | 3,900 |
| Limestone | 7,800 |
| MEBIOS particles | 220 |
| Particle diameters, $D_p$ | 2.7 mm $\sim$ 3.9 mm |
| Particle densities, $\rho_p$ | |
| Iron ore | $3.15 \times 10^3$ kg/m$^3$ |
| Coke | $1.05 \times 10^3$ kg/m$^3$ |
| Limestone | $2.57 \times 10^3$ kg/m$^3$ |
| MEBIOS particles | $2.98 \times 10^3$ kg/m$^3$ |
| Friction coefficient | |
| Particle-Particle, $\mu_p$ | 0.45 (before sintering) |
| | 1.0 (after sintering) |
| Particle-Bottom wall, $\mu_w$ | 0.30 |
| Poisson ratio, $\nu$ | 0.25 |
| Modules of elasticity, $E$ | $1.0 \times 10^7$ Pa |

$\mu_p$, $\mu_w$, $\nu$ and $E$ are used for all kinds of particles.

![Fig. 2. Particle size distributions in small particle sintering bed.](image)

![Fig. 3. Schematic diagram of melting zone.](image)
fied. 55% of the volume melted and the melting liquid was distributed equally to the iron ore particles contacted to this limestone particle which was removed instantaneously from the computational domain.

- [Coke particles of which content is 5% number based of whole particles]

When the top of the melting zone reached a coke particle center, the particle burned out and it was removed instantaneously from the computational domain.

The cohesion force $F_c$ which acted on the contact particles with the melting liquid film was calculated using Eq. (15) of the liquid bridge force which was the normal cohesion force.\(^{(13)}\)

\[
F_c = \gamma \alpha \sin \alpha \left[ \sin(\alpha + \theta) + \frac{d}{4} \left( \frac{1}{R_1} - \frac{1}{R_2} \right) \sin \alpha \right] ... (15)
\]

where $\gamma$ is the surface tension, $d$ is the solid particle diameter, that is $0.794 D_p$ for the equal particles, the averaged particle diameter was used for $d$ for the unequal particles and $\theta$ which is the contact angle between the liquid and the solid particle surface was assumed to be equal to zero in the present calculation, because $\theta$ usually is not large. Others are shown in Fig. 4 and Notation.

The Eq. (16) of Happel and Brenner\(^{(14)}\) gives the drag force $F_R$ which acts on approaching particles with the liquid film as shown in Fig. 4.

\[
F_R = 3 \pi \mu_{\text{lu}i} d \nu \beta \ldots (16)
\]

\[
\beta = \frac{4}{3} \sinh \phi \sum_{n=1}^{\infty} \frac{n(n+1)}{(2n-1)(2n+3)} \left[ \frac{2 \sinh(2n+1)\phi+(2n+1)\sinh 2\phi}{4 \sinh^2(n+1/2)\phi-(2n+1)^2 \sinh^2 \phi} \right] \frac{1}{d}.
\]

where $L$ is the distance between two particle surfaces, $\nu_{\text{lu}i}$ is the normal relative velocity between particles. The 5th terms in the series of $\beta$ in Eq. (16) were used, namely the terms for $n=1$ to 5. The increment of $\beta$ by the term for $n=5$ was less than 0.5%. $\gamma = 0.63 \text{ N/m}^{12}$ and the liquid viscosity $\mu_{l} = 0.06 \text{ Pa} \cdot \text{s}^{12}$ were used in Eq. (15) and Eq. (16) respectively. The resultant forces of $F_c$ and $F_R$ acting around the reference particle $i$ are $F_{ci}$ and $F_{ri}$ in Eq. (10).

2.5. Model of Particle Simulation in Sintering Process

Placing Large Particles (MEBIOS Particles)

The bed shrink and the void distribution were simulated under the circumstances that the large particles, which represented the mature layer in MEBIOS method in the sintering, were placed in the sintering bed. The diameter and the density of the large particle which was spherical were 12.0 mm and $2.98 \times 10^3 \text{ kg/m}^3$ respectively. 220 large particles were placed in the sintering bed. The mass ratio of the large particles to the small particles of which diameters were less than 3.9 mm was about 10%.

The packing fraction in the computational lattice in the large particle as shown by the black lattice in Fig. 5 was taken to be 0.75 of the most densely packing (rhombohedral packing) for equal particles. The gas is not able to flow in such a lattice because of the large drag force by the solid wall in the large particle. In the lattice including some part of a large particle and small particles as shown by the gray lattice in Fig. 5 the packing fraction was calculated by the linear proportion method between the packing fraction by the small particles and the gas, and the packing fraction (0.75) of the large particle. The gas velocity around the large particle assumed to be equal to the mean gas velocity in the lattices located in the large particle. $F_{\text{gas}}, F_{\text{lu}}$, $\text{St}_i$, $\text{St}_l$ for the large particle and the gas were calculated using the relative velocity between this mean gas velocity and the particle velocity at the large particle center.

In order to find contact particles efficiently, the partition with 12 mm edge, which was equal to the diameter of the large particle, for searching the contact point between large particles and for the contact point between a large particle and small particles was used in the present simulation. The partition with 4 mm edge, which was nearly equal to small particle diameter, for the contact point between small particles was used. The calculation using our two kinds of the partition run over about 25 times faster than that using the partition with 12 mm edge.

When a large particle contacted an iron ore particle in the melting zone, the cohesion force and the drag force due to the liquid bridge, which were calculated using Eq. (15) and Eq. (16), acted on these particles.

When the top of the melting zone reached the particle center, the angular velocity set to be zero, the cohesion force between contact particles was taken to become 10 times larger than the cohesion force by melting liquid and the friction coefficient was also taken to become larger to be 1.0 from 0.45 for the fixation of the particles after the sintering process.
3. Results and Discussion

3.1. Sintering Bed of Small Particles

3.1.1. Initial Packing State

The cubic packing based on the maximum particle diameter \(D_p = 3.9\, \text{mm}\) of the particles which were arranged to satisfy the particle number ratios that the iron ore particle was 85\%, the limestone particle was 10\% and the coke particle was 5\%, and to take account of the segregation in the vertical direction was made in the computational domain as shown in Fig. 6. 10\% of the particles in the cubic arrangement were erased to form naturally uniform packing using random number. Then the sedimentation started. When the particle velocities of whole particles in the bed became less than 1.0 mm/s through the sedimentation, it was presumed that the initial quiescent particle packing state was made in the sintering bed.

Three kinds of particles, iron ore, limestone and coke, were initially arranged as follows:

Method 1: According to the number ratios of these three kinds of particles, the particles of each kind were arranged with the equal separation. The uniform arrangement for each kind of particles was attained.

Method 2: According to the number ratios of these three kinds of particles, 66 300 particles of the iron ore, 7 800 particles of the limestone and 3 900 particles of the coke were arranged using the random number. The segregation within several percents for three kinds of particles existed in this arrangement of the initial particle bed.

Figure 6 shows the initial particle arrangements before the sedimentation using the Method 1. Figure 6(a) shows the distribution of three kinds of particles. Figure 6(b) shows particle size distributions. Figure 7 shows the initial particle packing state at 2.0 s after the sedimentation of the initial particle arrangements by the Method 1 started. Figure 8 shows the initial particle packing state at 2.0 s after the sedimentation of the initial particle arrangements obtained using Method 2 started. The particle locations in Figs. 7 and 8 were the initial values for DEM calculation in the sintering process.

3.1.2. Numerical Simulation for Sintering Process of Small Particles Bed

Figure 9 shows the calculated particle locations at various times in sintering bed of which initial particle arrangement is formed using Method 1. The uniform arrangement is attained. Two lines in this figure indicate the bottom and the top of the melting zone. Figure 10 shows the upper part of Fig. 9(d) to see the detail of the bed structure. In the melting zone 50\% of the ore particle volume melts and the diameter \(D_p\) reduces to 0.794\(D_p\). The separation between the solid surfaces of melted ore particles decreases by the packing due to mainly the weight of particle bed above them. Then the packing state of the particles becomes to be denser. The diameter including the melting liquid surface of ore particle which contacts limestone becomes larger by the liquid of the melted limestone. The cohesion force acts on the particles through the liquid film. Then the collision rate between particles increases and the agglomerate is easily
formed. The local void grows by the agglomeration of particles and the porous structure is formed as shown in the upper part of the bed in Fig. 10. The particles sink into the void through the sedimentation and the packing by the weight of the bed. The void in the upper part of the bed is not buried by particles because the force to pack the particles by the weight of the bed is small. Therefore the large void spaces exist in the upper part of the bed as shown in Figs. 9 and 10. These effects reduce the bed height of the sintering bed, that is the bed shrink, according to the moving downward of the melting zone as shown in Fig. 9.

The change of the bed height at each time gives the bed shrink velocity. For examples the mean bed shrink velocity during the initial 4 s was 9.0 mm/s and that during 16 to 20 s was 2.8 mm/s after the sintering process began. The bed shrink velocity decreased with the moving downward of the melting zone. One of the reasons for this is that the weight of the particle bed increases with increasing the bed height. The iso-contours of the packing fraction in Fig. 11 show that the packing fraction becomes larger with going downward in the bed. It is hard that the high packing fraction changes to the higher packing state, because the mobility of the particles with the higher packing fraction is smaller. In the present calculation the final bed shrink ratio which is defined as the ratio of the final bed height and the initial bed height was 82% which agrees with that measured in the actual sintering furnace. The relative cohesion force in the upper part of the bed which consists of small particles is larger than that in the lower part of the bed which consists of large particles because the relative cohesion force between the small particles is larger than that between large particles. The maximum and the averaged cohesion forces between the iron ore particles of \(D_p/\mu_{1005} = 2.7 \text{ mm}\) in the melting zone at \(T/H_{11005} = 4.0 \text{ s}\) were 4.5 and 2.4 times of the particle weight respectively, on the other hand these for the iron ore particle of \(D_p/\mu_{11005} = 3.9 \text{ mm}\) in the melting zone at \(T/H_{11005} = 20.0 \text{ s}\) were 2.1 and 0.9 times of the particle weight respectively. The large cohesion force becomes to be easier to agglomerate particles and to shrink the bed.

Figure 12 shows the calculated particle locations in sintering bed of which the initial particle arrangement is formed using Method 2. In this case the segregation within several percents for three kinds of particles exists in the initial particle bed. The calculated results indicate that the large scale crack appears in the bed after the sintering. It is obvious that the number density of the iron ore particles in the zone indicated by the dotted line in Fig. 12 is higher than those in the other areas in the bed. The number based contents of the iron ore particles, the limestone particles and the coke particles were 93%, 4% and 3% respectively which were calculated for 3 800 particles sampled in the zone indicated by the dotted line. On the other hand the number based contents of the iron ore, the limestone and the coke in the zone adjacent to that indicated by the dotted line in Fig. 12 were 84%, 11% and 5% respectively. Num-

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ber of the contact points among the iron ore particles in the circle by the dotted line was about 18% larger than that in the adjacent zone. The gap of the particle motions occurs between the zones of which the content and the contact number are largely different. Then the gap separates the contact particles and the crack appears. The separation of the contact points among particles, in other words the crack, cannot be seen by naked eyes at \( T/H_1 \approx 8.0 \) s (Fig. 12(b)), although the contact points have begun to separate at the period. As shown in Fig. 12(c) the crack can be seen by naked eyes at \( T=16.0 \) s. After that the crack grows as shown in Fig. 12(d).

The vertical zones in which the number densities of the iron ore particles were higher in the bed appeared in the areas where \( X=90 \) mm and \( X=200 \) mm, and \( Z=50–170 \) mm. The number based contents of the iron ore particles, the limestone particles and the coke particles were 89%, 7% and 4% respectively which were calculated for 3,200 particles sampled in these zones. However the vertical cracks did not appear in the boundaries near the zones. Since the long side of the melting zone in the present simulation was horizontal, the separation of the contact points, in other word crack, more easily occurred in the segregation boundary stretched horizontally than in that stretched vertically. In actual sintering furnaces vertical cracks occur. The crack in an arbitrary direction could be simulated by considering the precise configuration of the melting zone and other exact sintering conditions.

3.2. Sintering Bed Placing Large Particles (MEBIOS Particles) in Small Particle Bed

3.2.1. Initial Packing State

Sintering process in the particle bed of which the initial small particle arrangement was formed using Method 2 and the large particles were placed in the small particle bed has been simulated. Figure 13 shows the initial particle bed (packing state) at 2.0 s after the sedimentation of the initial small particle arrangements obtained using Method 2. Figure 14 shows the initial packing state of the particle bed at 3.6 s after the free settling through \( Z=750 \) mm.

Fig. 12. Calculated instantaneous particle locations in the sintering bed. Dotted circle shows the high content region of iron ore particles.

Fig. 13. Calculated initial particle packing state placing large particles in cubic lattices at 2.0 s after the sedimentation of the initial particle arrangements obtained using Method 2.

Fig. 14. Calculated initial particle packing state at 3.6 s after the free settling through \( Z=750 \) mm.
3.2.2. Sintering Process of Particle Bed Placing Large Particles among Small Particles

The calculated locations of small and large particles arrayed in the cubic lattice, small and large particles arrayed using the random number and small particles without large particle at $T=18.0\,s$ after the sintering started are shown in Figs. 15(a)–15(c), respectively. These calculated results show that the shrinks of the beds with the large particles are smaller than that of the bed without the large particles. The reasons are that the large particles do not change the particle volume and also the high void region around the large particles is formed.

As shown in Fig. 15 the crack does not occur in the particle bed placing the large particles even if the initial particle arrangement is formed using Method 2. In this case the segregation for three kinds of particles usually exists in the initial particle bed. This is because the large scale zones of which the content and the contact number are largely different are cut off by the large particles and the small crack originated from the separation of contact points between iron ore particles does not grow by the existence of the large particles.

The comparison of Fig. 16(a) with Fig. 16(b) shows that the low number density areas are formed around the large particles before sintering, and after the sintering the high number density areas on the large particles and the void areas under the large particles are formed. These results agree with the experimental test of the sintering behavior of the bed placing large particles by Kamijo et al.\textsuperscript{15}) The density of the large particle is $\rho_p=2.98 \times 10^3\,\text{kg/m}^3$ and the density of the iron ore particle is $\rho_p=3.15 \times 10^3\,\text{kg/m}^3$. Therefore the large particles relatively ascend among the small particles. These ascents formed the voids under the large particles. The void grew due to the agglomeration among iron ore particles which were near and did not touch the large particles.

Figure 17 shows the gas velocity vector diagrams at 18s after the sintering began. The gas flows to the area under the large particle because the void under the large particle is high. The maximum gas velocity under the large particles was 3.0 m/s which were 4 times larger than the superficial velocity of the bed. The maximum velocity in the small particle bed was about 2 m/s. Such a high gas velocity would make the higher void area under the large particles.

Figure 18 shows the contours of the gas pressure in the particle bed with sucking gas at the constant superficial velocity $U_0=0.68\,\text{m/s}$ as shown in Fig. 1. The pressure losses in the beds placing the large particles shown in Figs. 18(a) and 18(b) are smaller than that in the small particle bed shown in Fig. 18(c). The high void regions formed over the beds placing large particles cause these low pressure losses. Therefore the large particles placing in the bed improve the ventilation in the bed. Both pressure losses which were about 900 Pa over the sintering bed placing large particles and about 1 000 Pa over the small particle sintering bed were about half of that in the actual sintering bed. This is because the present simulation does not consider the effects
of the powder yielding by compaction and the melting liquid.

4. Conclusion

The motions of the particles and the gas in the sintering bed were simulated by the simultaneous calculation of the Lagrangian DEM equations and Navier–Stokes equations for the gas based on the simple sintering model in which the phase change of particles and the cohesion forces due to the liquid bridges among particles were considered. As the result the following concluding remarks were obtained.

(1) The bed shrink rate decreased with the moving downward of the melting zone. One of the reasons for this is that the weight of the particle bed increases with increasing the bed height. The iso-contours of the packing fraction in Fig. 11 show that the packing fraction becomes larger with going downward in the bed. It is hard that the high packing fraction changes to the higher packing state because the mobility of the particles with the high packing fraction is smaller.

(2) When the uniform initial arrangement of particles is attained, the nearly homogeneous porous bed is obtained. On the other hand the gap of the particle motions occurs between the zones of which the content and the contact number are largely different. The gap separates contact particles and the crack appears.

(3) The shrinks of the beds with the large particles are smaller than that of the bed without the large particles. The reasons are that the large particles do not change the particle volume and also the high void region around the large particles is formed.

(4) The crack does not occur in the particle bed placing the large particles. The large scale zones of which the content and the contact number are largely different are cut off by the large particles and the small crack originated from the separation of contact points between iron ore particles does not grow by the existence of the large particles.

(5) After the sintering the high number density areas on the large particles and the void areas under the large particles are formed. This is because the large particles with smaller particle density relatively ascend among the small particles with the larger particle density. The void grows due to the agglomeration among iron ore particles which are near and do not touch the large particles.

(6) The pressure losses in the beds placing the large particles are smaller than those in the small particle bed. The high void areas formed in the beds placing large particles cause these low pressure losses.

Nomenclature

\( C_L \): Lift coefficient (–)
D_i: Damping force vector at contact point of particle i and j (N)
D: Width of computational domain (m)
d: Solid particle diameter of iron ore in melting zone (m = 0.794D_i) (m)
D_p: Particle diameter (m)
E: Modulus of elasticity (Pa)
F_i: Contact force vector at contact point of particle i and j (N)
F_C: Resultant force vector of F_C acting around particle i (N)
F_C: Cohesion force due to liquid bridge between two particles in melting zone (N)
F_D: Drag force vector acting on particle i (N)
F_L: Lift force vector acting on particle i (N)
F_g: Gravitational force vector acting on particle i (N)
F_R: Resultant force vector of F_R acting around particle i (N)
F_R: Drag force acting on approaching particles with liquid film in melting zone (N)
I_p: Inertia moment of particle (kg m²)
L: Distance between two particle surfaces (m)
M: Parameter of fluid friction torque (rad-
M: Moment vector due to contact force at contact point of particle i and j (N m)
M_D: Moment due to damping force at contact point of particle i and j (N m)
M_F: Fluid friction torque vector acting on particle i (N m)
m_p: Particle mass (kg)
N: Number of particles per unit volume (m⁻³)
\( n \): Term number of series solution of \( \beta \) (°)
P: Static pressure (Pa)
\( p \): Nondimensional static pressure (\( =P/(\rho U_0^2) \)) (°)
R_1: Dimension of liquid bridge (m)
R_2: Dimension of liquid bridge (m)
R_e: Particle Reynolds number (\( =\rho \omega/D_p \) (rad/s)) (°)
R_{e,pa}: Particle Reynolds number on rotation (m)
St: Nondimensional interaction term vector due to fluid drag force defined by Eqs. (3) and (4) (°)
St_L: Nondimensional interaction term vector due to fluid lift force defined by Eqs. (6) and (8) (°)
T: Time (s)
\( t \): Nondimensional time (\( =TU_0/D \)) (°)
U: Gas velocity vector (m s⁻¹)
\( u \): Nondimensional gas velocity vector (\( =1/U_0)U \) (°)
U_0: Superficial suction gas velocity (m s⁻¹)
\( \mu_p \): Normal relative velocity between particles (m s⁻¹)
\( X, Y, Z \): Cartesian coordinates (m)

Greek letters
\( \alpha, \theta \): Contact angles of liquid bridge between particles (rad)
\( \beta \): Correction factor of drag force acting on approaching particles with liquid film (°)
\( \epsilon \): Void fraction (°)
\( \phi \): Parameter of correction function \( \beta \) (°)
\( \gamma \): Surface tension of liquid film (N/m)
\( \mu \): Gas viscosity (Pa s)
\( \mu_i \): Viscosity of liquid film (Pa s)
\( \mu_w \): Friction coefficient (particle–particle) (°)
\( \mu_{nn} \): Friction coefficient (particle–bottom wall) (°)
\( \nu \): Poisson ratio (°)
\( \xi(\epsilon), \xi_0(\epsilon) \): Correction factors of drag and lift forces in multi-particle system (°)
\( \rho \): Gas density (kg m⁻³)
\( \rho_p \): Particle density (kg m⁻³)
\( \Omega \): Particle angular velocity vector (rad/s)
\( \Omega^* \): Relative velocity ratio of rotation and translation (\( =((D_p/D)(1/2)\n\times \nabla \times -\omega)/(2\n\times -\omega)) \) (°)
\( \omega_p \): Nondimensional particle angular velocity vector (\( =((D/U_0)\Omega_p) \)) (°)
\( \nabla \): Nabla operator (°)
\( \times \): Vector product (°)
\( :: \): Scalar product (°)

Subscript
\( i,j \): Particle number
\( p \): Particle

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