Heat Transfer Analysis of the Mosaic Embedding Iron Ore Sintering (MEBIOS) Process

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Using computational fluid dynamics software, two-dimensional (2D) and three-dimensional (3D) simulation models for simulating the mosaic embedding iron ore sintering (MEBIOS) process were developed on the basis of the concept of the multiply shared space (MUSES) method. When one pellet (diameter: 15 mm) was placed at the centre of a sintering bed, the estimated time variations of temperature at the centre and surface of the pellet by both the 2D and 3D simulations were similar to the corresponding experimental results. The calculated cooling rate of the pellet was comparatively high; however, it could be improved further by introducing the fraction of closed pore in the bed in the simulation model.

It was supposed that the 2D simulation of the MEBIOS process was quite effective in decreasing calculation cost; therefore, in the case that several pellets were distributed in lattice and staggered alignments throughout the bed, the 2D model was used for calculating the time variations of temperature at the centre of the pellets. The calculated results showed that the sintering process could not continue when the pellets were distributed in the staggered alignment and the distance between pellet centres was 30 mm. On the other hand, changing the distance between the pellets distributed in the lattice alignment had little effect on the sintering process, and the process accelerated by approximately 300 s due to the high gas velocity around the pellets.

KEY WORDS: MEBIOS process; computational fluid dynamics; MUSES method; numerical simulation; lattice alignment; staggered alignment; porosity.

1. Introduction

Recently, the use of pisolite and marramamba ores (whose combined water content is comparatively high) found in Australia has increased dramatically because of a shortage of high-grade iron ores and an increase in transport cost. Furthermore, the average particle size of iron ores is expected to become smaller in the future. In order to maintain international competitive power of the Japanese steel industry and to minimize environmental effects of iron making processes, it is essential to develop the agglomeration technology of such low-grade iron ores, which in turn would ensure their effective use.

The ‘mosaic embedding iron ore sintering’ (MEBIOS) process is a new method for iron ore sintering, which aims to efficiently use low-grade ores and ensure high productivity of sinter by separating a sintering bed to the induction bed and green pellets of larger size. The purpose of the induction bed is to induce sufficient heat transfer downward the bed, and the pellets are composed of fine ore particles, where solid sintering proceeds. The objective of the present study is to determine the optimum location, number, and size of large pellets, which are important parameters for designing an efficient MEBIOS process. These parameters are determined by simulating the heat transfer using the two-dimensional (2D) and three-dimensional (3D) models developed in computational fluid dynamics (CFD).

2. Simulation Model

2.1. Overview of Simulation Model

In order to simulate the heat transfer occurring in the sintering bed, the 2D and 3D simulation models were developed using a CFD software. In the simulation models, the MEBIOS bed, which is composed of the induction bed and the large green pellets distributed in it, was treated as a porous material having different chemical compositions and porosities.

The calculation region was divided into a number of control volumes by the finite volume method. Equations of continuous heat and mass transfer in the gas phase and the energy conservation equation of the solid phase were solved numerically. Equations (1) and (2) given below are the basic conservation equations of the gas and solid phases, respectively.

Gas phase:

\[
\frac{\partial}{\partial t} (\rho_g \phi_g) + \frac{\partial}{\partial x_i} \left( \rho_g v_i \phi_g - \Gamma_g \frac{\partial \phi_g}{\partial x_i} \right) = S_{\phi_g} \quad \ldots \ldots \ldots \ldots (1)
\]
Solid phase:

\[ \frac{\partial}{\partial t} ((1-\varepsilon) \rho_s C_{p,s} T_s) - \frac{\partial}{\partial x_i} \left( (1-\varepsilon) \lambda_s \frac{\partial T_s}{\partial x_i} \right) = S_{T,s} \] .................................(2)

where \( \varepsilon, \rho_s, \lambda_s, \) and \( \phi_s \) are the porosity of the bed, gas density, transfer variable in the gas phase, gas velocity, diffusion coefficient of \( \phi_s \), source term, solid density, solid specific heat capacity, solid temperature, heat conductivity of solid, and thermal source \( =-S_{T,s} \), respectively. The term \((1-\varepsilon) \lambda_s \) in Eq. (2) denotes the apparent heat conductivity of the bed. To express the heat conductivity, the following experimental formula of the apparent thermal diffusion coefficient \( \alpha \) of the compacted hematite powder, given by Shibata et al.\(^1\) was used:

\[ \alpha = 1.3 \times 10^{-5} \text{ (m/s)} \] .................................(3)

Gas flow in the simulation model was assumed to be incompressible laminar flow. The Ergun equation\(^3\) was used as the momentum source in the momentum conservation equation of the gas phase (Eq. (4)); this equation provides the loss of pressure of air flow in a packed bed.

\[ \frac{\Delta P}{L} = 150 \frac{(1-\varepsilon)^2}{\varepsilon^3} \frac{\mu_g}{(d_p)^2} v_g + 1.75 \frac{(1-\varepsilon)}{\varepsilon} \frac{\mu_g}{d_p} (v_g)^2 \] ...........................................(4)

where \( \Delta P, L, \mu_g \) and \( d_p \) are the pressure loss, height of a packed bed, gas viscosity, and solid particle diameter, respectively.

Further, with reference to chemical reactions occurring in the sintering process, the following chemical formulas and reaction heats were incorporated into the conservation equations of expected chemical species. Reactions 1–5 are those occurring during coke burning, thermal decomposition of limestone, generation and melting of calcium ferrite, solidification of calcium ferrite melt, and vaporization-condensation of water, respectively.

(Reaction 1) \( C(s) + O_2(g) \rightarrow CO_2 \) (271.8 kJ/mol)
(Reaction 2) \( CaCO_3(s) \rightarrow CaO(s) + CO_2(g) \) (-161.3 kJ/mol)
(Reaction 3) \( CaO(s) + 2Fe_2O_3(s) \rightarrow CaO \cdot 2Fe_2O_3(l) \) (-188.6 kJ/mol)
(Reaction 4) \( CaO \cdot 2Fe_2O_3(l) \rightarrow CaO + 2Fe_2O_3(s) \) (188.6 kJ/mol)
(Reaction 5) \( H_2O(l) \rightarrow H_2O(g) \) (±40.71 kJ/mol)

By taking into account mass changes of chemical species in these reactions, the porosity of the sintering bed was assumed to change step by step, as shown in Eq. (5). Here, \( r_i \) and \( \Delta t \) are the consumption or generation rate of the \( i \)th chemical component and the time step in calculation, respectively. The subscript ‘old’ denotes the previous time step.

\[ \rho_s(1-\varepsilon) = \rho_{s,old}(1-\varepsilon_{old}) - \sum r_{i,old} \Delta t ...............(5) \]

Because it was expected that a comparatively high porosity region existed around the boundary of the induction bed A and large pellets B, the semi-empirical porosity distribution given in Eq. (6)\(^5\) was set in the beginning. Figure 1 shows an image of the initial porosity distribution. When the initial porosities of the induction bed and the pellets were 0.4 and 0.25, respectively, the porosity around a pellet attained approximately 0.90.

\[ \varepsilon_{0,trans} = \varepsilon_{0,A} + (0.95 - \varepsilon_{0,A}) \exp \left( \frac{R_p - r_p}{d_{p,A}} \right) \] .................................(6)

where \( \varepsilon_{0,A}, R_p, d_{p,A} \) and \( r_p \) are the initial porosity of the induction bed A, radius of the large pellets B, distance from a pellet centre, and diameter of particles in the induction bed, respectively.

We have previously presented some calculation results, e.g. calculation in the case that one pellet was inserted at the centre of the bed and four pellets were placed in line, by using the 2D axisymmetric simulation model built on the basis of the abovementioned assumptions.\(^4\) Since this 2D model cannot be applied for non-axisymmetric and 3D simulations, in the present study, we developed a simulation model on the basis of the multiply shared space (MUSES) method.\(^5\)

2.2. Modelling by MUSES Method

The MUSES method can be easily applied to flows and heat and mass transfers occurring in a porous material, in which gas and solid phases are modelled independently and only the convective heat transfer between both phases is considered. Since the CFD software used originally did not have a function for calculating fluid dynamics and heat and mass transfer in porous materials, we developed the simulation model using the MUSES method by incorporating such functions in the CFD solver; this incorporation was achieved by programming in the computational language of the CFD solver.

Figure 2 shows the concept of the new model. The calculation regions in the gas and solid phases were identical, and the porosity, solid ratio, and physical properties in these phases were established. Hot gas at a prescribed temperature was released from a gas inlet over only the gas phase region. The convective heat transfer between the gas and solid phases was calculated by assuming that the temperature difference between the control volumes at the same
position in each phase acted as a driving force. \( h_{ex}, A_{ex}, T_g \), and \( T_s \) in Fig. 2 denote the heat transfer coefficient, specific area of heat transfer, gas temperature, and solid temperature, respectively.

3. Heat Transfer Analysis in the Case of One Pellet Placed at the Bed Centre

3.1. Initial Conditions

After developing the 2D and 3D simulation models, one large pellet was placed at the centre of the induction bed, and calculations were performed using the models. The modelling of the MEBIOS bed was carried out according to the experimental conditions. That is, the pellet size and the diameter and height of the induction bed were set to 15, 70, and 400 mm, respectively (Fig. 3). Each control volume was a square (2D) or a rectangular solid (3D), and its size was determined by dividing the calculation region into blocks with dimensions of 65 (width)×108 (height)×50 (depth) (only in the case of 3D model). It means the size of each control volume was 1.1 mm (width)×3.7 mm (height)×1.4 mm (depth). The region around the pellet was also divided in the same size, since the calculated results were little different from the cases that 2 or 5 times finer control volumes were used around the pellet. The time step was 0.001 s up to 0.01 s, 0.01 s up to 1 s, 0.1 s up to 10 s and 0.5 s subsequently. The calculations were continued up to 2000 s. The initial porosities, particle diameters, and chemical compositions of the induction bed A and pellets B are summarized in Table 1. The temperature and superficial velocity of the hot gas released from the gas inlet were set to 1100°C and 1.0 m/s, respectively. In addition, burning time, heat loss from a sinter-pot wall, and gas pressure at the gas outlet were assumed to be 90 s, −2.5 W/m², and −300 mmH₂O, respectively.

3.2. Results and Discussion

The calculated time changes of the solid phase temperature at distances of 100, 200 (centre of the pellet), and 300 mm from the gas inlet on the centreline of the MEBIOS bed are shown in Fig. 4. The black and grey solid lines show the results calculated by the 2D and 3D simulation models, respectively. This figure also shows the experimental results (exp) obtained under the same conditions.

From Fig. 4, it is clear that the calculation results obtained by both the 2D and 3D simulations are similar to the experimental results, particularly in terms of the starting time of increase in temperature and the attained maximum temperature. Therefore, it would be quite effective to perform simulation as follows: (1) the 2D model should be first used to perform calculations under changing conditions and (2) some select calculations should be performed using the 3D model by considering the obtained trend of

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**Table 1.** Initial conditions used for the calculations.

|                | Porosity | Particle size | Fe₂O₃ (mass%) | C (mass%) | CaCO₃ (mass%) | H₂O (mass%) |
|----------------|----------|---------------|---------------|-----------|---------------|-------------|
| Induction bed: A | 0.40     | 1.0           | 75            | 5         | 12            | 8           |
| Large pellet: B  | 0.25     | 0.50          | 100           | 0         | 0             | 0           |

(pellet: 15)
temperature change. This process would lead to a significant reduction in the calculation cost. The calculated cooling rates of the pellet were higher than the experimental cooling rates; however, better results were obtained by the 3D simulation because hot gas was passed over the pellets three-dimensionally. A measure that could be taken to estimate the cooling rate with greater accuracy is to introduce the fraction of closed pores in the bed in the simulation models, since all pores in each bed are assumed to be open pores.

In the developed simulation model, the porosity was changed depending on the generation and consumption of chemical components; however, the change did not consider the shrinkage of the sintering bed or uneven distribution of pores. Furthermore, the initial porosity distribution around a pellet was obtained by the semi-empirical equation (Eq. (6)). Therefore, it is essential to develop more phenomenological models of porosity distribution and its generation mechanism since an increase in the gas velocity around a pellet has a significant effect on the sintering behaviour. The discrete element method (DEM) has been found to be a promising modelling method. In the future, our simulation model and the DEM model developed by Umekage et al. could be combined, and sequential exchanges of porosity and heat and mass change data between them could be simulated. This would lead to the development of an advanced simulation model of the MEBIOS process. For this purpose, the decision of a time step would become a difficult problem because a time step of less than 10^{-4}s is usually used for DEM calculations. To resolve this problem, it is suggested that the calculation region be simplified and a 2D model be used for calculations.

Figure 5 shows the calculated time changes of temperature at the surface and centre of pellets. The differences between temperatures at the pellet surface and pellet centre calculated by the 2D and 3D simulations were 70 and 103°C, respectively. Because the experimental differences obtained under the same conditions were between 30 and 60°C, the result of the 2D simulation was closer to the experimental. One possible reason for this is that the temperature of the pellet at the surface in the 3D simulation was slightly higher than that in the 2D simulation.

4. Heat Transfer Analysis in the Case of Several Pellets Distributed in the Bed

4.1. Effect of Distance between the Pellet Centres on Sintering Process

As shown in the previous section, the temperature change in the MEBIOS bed estimated by the 2D simulation was fairly accurate. In this section, the calculation of pellet temperatures in the case of several aligned pellets placed throughout the bed by using the 2D simulation model is discussed.

In order to understand the effect of the distance \( L_p \) between pellet centres on the sintering process, \( L_p \) was changed to 30, 60, and 90 mm in the 2D simulation model. The pellet diameter and the height and width of the bed were set to 15, 690, and 30 mm, respectively. The distance between the gas inlet and the centre of the first pellet was fixed to 120 mm, and the distance between the gas outlet and the centre of the last pellet was fixed to 30 mm. These values imply that the number of aligned pellets in the cases of \( L_p = 30, 60, \) and 90 was 19, 10, and 7, respectively. Figure 6 shows the calculation regions of the simulation models. Because a periodical boundary was set in the direction of the bed width, the distance between the pellet centres became 30 mm. The calculation region was separated into control volumes with dimensions of 20 (width)×276 (height). The calculations were continued up to 4000 s. Other calculation conditions were the same as those in the case of one pellet in the bed.

Figure 7 shows the calculated time changes of the temperature of the pellets at distances of 120, 300, 480, and 660 mm from the gas inlet. The numbers in parentheses are the distances between the pellet centres. The black and grey solid lines show the cases of \( L_p = 30, 60, \) and 90 was 19, 10, and 7, respectively. The dotted line shows the case of the distance of 90 mm.

From Fig. 7, it is clear that the sintering process in the MEBIOS bed was completed successfully and the maximum solid temperature increased downward the bed up to approximately 1 450°C. The effect of the distance between the pellet centres on the sintering process was small; how-
However, the time required to attain the maximum temperature was less when \( L_p = 90 \) mm. This speed of sintering, which was higher than those in the cases of \( L_p = 30 \) and \( 60 \) mm, could be attributed to the following two factors: (1) the presence of a pellet in the bed leads to an increase in the heat transfer rate due to the increase in the gas velocity around the pellet and (2) heat supply decreases because the pellet does not contain coke.

### 4.2. Effect of Pellet Alignment on Sintering Process

In order to examine the effect of pellet alignment on the sintering process, the case in which the pellets were in staggered alignment was simulated. Calculations in this case were performed using the 2D model. Figure 8 shows the calculation regions in these cases. In these cases as well, \( L_p \) was set to 30, 60, and 90 mm. The width of the bed was 60 mm and the periodical boundary was set at both its edges; therefore, the distance between the centrelines of aligned pellets in the direction of the bed width was 30 mm. The control volumes had dimensions of 40 (width)×276 (height). The calculations were continued up to 4000 s. Other calculation conditions were the same as those in the previous cases.

Figure 9 shows the calculation results of time changes of temperatures at pellet centres at distances of 120, 300, 480, and 660 mm from the gas inlet. The positions of the pellet centres are shown in the figure. Figures 10(a) (lattice alignment) and 10(b) (staggered alignment) show the temperature distributions of the solid phase at 1750 s in the case that \( L_p \) was 30 mm and the temperature difference is clear in the whole region.

From Fig. 9, it can be observed that in the case of \( L_p = 30 \), the pellet temperature decreased from the gas inlet downward the bed and the sintering process failed. This failure may be attributed to the fact that many distributed pellets did not contain coke, which in turn led to insufficient heat supply. When \( L_p \) was 60 or 90 mm, the maximum temperature was expected to increase downward the bed and become up to approximately 1450°C. In this case, the sintering speed at \( L_p = 60 \) was slightly higher than that at \( L_p = 90 \); this result is different from that in the case of pellets distributed in the lattice alignment. Therefore, the optimum distance between pellets placed in the staggered alignment was 60 mm.

By arranging the pellets in the staggered alignment, the maximum temperature of the pellet centre was almost the same as that when the pellets were arranged in the lattice alignment, but the time required to attain the maximum...
temperature at a distance of 660 mm from the gas inlet prolonged by approximately 300 s. This is because the gas velocity around the pellets decreased (see Fig. 11). Figure 11 shows the synthesized gas velocity distributions in the steady state in the cases of the lattice (Fig. 11(a)) and staggered alignments (Fig. 11(b)). In order to examine the effect of the type of alignment on the gas flow, the superficial gas velocity and temperature at the gas inlet were set to 0.3 m/s and 20°C, respectively. The calculated maximum velocities were 1.6 m/s (lattice) and 1.0 m/s (staggered). Therefore, it is desirable to adopt the lattice alignment in the MEBIOS process.

In the present study, the distance between pellets in the direction of the bed width was fixed to 30 mm in all calculations; however, when this distance would become very small, insufficient heat would be generated. Conversely, the effect of an increase in the gas velocity around a pellet would decrease if this distance would be very large. This implies that there exists an optimum distance between pellets in the direction of the bed width, at which sufficient heat would be generated.

5. Conclusions

By using computational fluid dynamics software, 2D and 3D simulation models for simulating the mosaic embedding iron ore sintering (MEBIOS) process were developed on the basis of the concept of the multiply shared space (MUSES) method. Time variations of temperature at the centre and surface of the pellets were calculated for the case in which one pellet was placed at the bed centre and the case in which several pellets were distributed in the bed. In the latter case, the distance between the pellet centres and their alignment were changed to examine their effects on the sintering process.

In the case of placing a single pellet at the bed centre, the estimated patterns of temperature change obtained using both the 2D and 3D simulation models were approximately consistent with the experimental patterns. Therefore, for decreasing the calculation cost, it would be quite effective to perform 2D simulations firstly in changing some conditions, and then, several selected calculations using the 3D model should be examined. The cooling rate of pellets was calculated to be high, since all the pores of each bed were assumed to be open pores. This rate could be improved further by introducing the fraction of closed pores in the bed in the simulation model.

The 2D simulation was performed in the case that several pellets were distributed in the bed. The calculation results showed that the sintering process failed when the pellets were distributed in the staggered alignment and the distance between the pellet centres was 30 mm. On the other hand, when the pellets were distributed in the lattice alignment, changing the distance between them had little effect on the sintering process, and the process accelerated by approximately 300 s. This was because when the pellets were distributed in the lattice alignment, the gas velocity around them was higher.

In order to improve the accuracy of the simulation results obtained by the developed model, it is essential to develop more accurate models of porosity distribution and its generation mechanism, e.g. by using the discrete element method (DEM), since the gas velocity around a pellet has a significant effect on sintering behaviour.

**Nomenclature**

- \( A_g \): Specific area of heat transfer (m²)
- \( C_p \): Specific heat capacity of solid (J/kg·°C)
- \( d_r \): Particle diameter (m)
- \( h_{tr} \): Heat transfer coefficient (W/m²·°C)
- \( L \): Height of packed bed (m)
- \( \Delta P \): Gas pressure loss of packed bed (Pa)
- \( S_{ex} \): Source term in energy conservation equation of gas phase (J/s)
- \( S_{ph} \): Source term in energy conservation equation of solid phase (J/s)
- \( T_g \): Gas temperature (°C)
- \( T_s \): Solid temperature (°C)
- \( v_g \): Gas velocity (m/s)
- \( \alpha \): Apparent thermal diffusivity of bed (m²/s)
- \( \Gamma_g \): Diffusion coefficient of \( \phi_g \)
- \( \varepsilon \): Porosity of bed (—)
- \( \lambda_g \): Heat conductivity of solid (W/m·°C)
- \( \mu_g \): Gas viscosity (m²/s)
- \( \rho_g \): Gas density (kg/m³)
- \( \rho_s \): Solid density (kg/m³)
- \( \phi_g \): Transfer variable in gas phase

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