제철 소결공정에 대한 단입자 연소 모델의 응용

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Application of Intra-particle Combustion Model for Iron Ore Sintering Bed

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ABSTRACT

Operation parameters for large scale industrial facility such as iron making plant are carefully selected through elaborate tests and monitoring rather than through a mathematical modeling. One of the recent progresses for better energy utilization in iron ore sintering process is the distribution pattern of fuel inside a macro particle which is formed with fines of iron ore, coke and limestone. Results of model tests which have been used as a basis for the improved operation in the field are introduced and a theoretical modeling study is presented to supplement the experiment-based approach with fundamental arguments of physical modeling, which enables predictive computation beyond the limited region of tests and adjustment. A single fuel particle model along with one-dimensional bed combustion model of solid particles are utilized, and thermal processes of combustion and heat transfer are found to be dominant consideration in the discussions of productivity and energy utilization in the sintering process.

Key Words : solid bed, combustion model, iron ore sintering bed, numerical simulation, coke late addition

기 호 설 명

COG	coke oven gas
LA	late addition
f	particle porosity
C_{O_2}	oxygen concentration
D_{eff,O_2}	effective diffusion coeff of O_2
ε	volume fraction of the solid
$\dot{M}_{s,k,r_s}$	loss rate per unit volume for the k component
$\dot{M}_{s,r_s}$	mass loss rate per unit volume
ρ_s	overall density of the particle
r_s	reaction number
T_s	local temperature of the solid phase
$C_{p,s}$	overall heat capacity of the solid
λ_s	overall heat conductivity
ΔH_r	heat of reaction
$m_{s,k}$	mass fraction of solid component k

1. Introduction

An iron ore sintering process is applied to produce large particles (typically >30mm) of iron ore with appropriate metallurgical properties required in a blast furnace. As shown in Fig. 1, a raw mix of iron ore, coke,

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limestone, and return fines is processed in a drum with spray water to form pseudo-particles of several millimeters in diameter. These particles are fed on a traveling grate to form a bed. Top of the bed is then exposed to a flame of COG (coke oven gas) burner to commence burning of the fuel inside the bed material. Air is supplied to the bed by a down draft suction fan. The combustion zone formed at the top propagates downward as the bed is slowly traveling along the bed of approximately 100m in length for 30-60minutes. The bed is 4-6m in width and 0.4-0.8m in depth. Combustion of coke portion inside each particle is accompanied by moisture evaporation and re-condensation, melting of limestone and sintering of agglomerated aggregate. In the initial stage of the solid-gas reaction, solid-gas convection plays an important role for drying and heating up of the pseudo particles. Coke combustion begins when the temperature of the particle is high enough, but limestone decomposition is competing with coke combustion in the initial stage. After limestone decomposition is completed and temperature of the solid material becomes higher than the combustion gas, solid-gas convection reverses its direction. The engineering issues of sintering process are how to increase productivity to process as much iron ore from the given facility; how to maintain quality of the sintered ore (structural size and strength); and how to minimize energy consumption during the process. Productivity of the sintering plant is defined as the useful products (which is larger than 5mm in size after a crushing process) per unit area of the bed, as is defined in Eq. (1).

$$\text{Productivity} = \frac{+5\text{mm Output}}{\text{Bed Area} \times \text{Sintering Time}} \quad (\text{ton/m}^2/\text{day})$$

Sintering time means a whole process time and is defined as the time when the temperature of the bottom of the bed reaches a peak. In order to improve the productivity, careful control of two crucial parameters related to solid fuel combustion is required. One is propagation speed of the combustion zone, which determines the sintering time. The other is thickness of the combustion zone, which is exhibited conceptually in Fig. 1. If combustion zone is excessively thick, it decreases gas permeability of the sintering bed then makes a negative effect on the strength of the product, which will decrease numerator of Eq. (1).

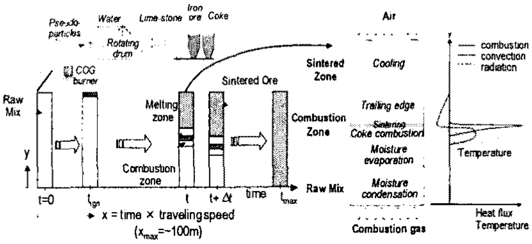


Fig. 1 Schematic of sintering process in the steel industry

It is of great interest to reduce fuel consumption in the sintering process without any loss of productivity. Recently, many effective measures were applied to improve productivity and quality, and to reduce fuel consumption, such as replacement of coke by coal [1], intensifying granulation, control of fuel grain size, and separate addition of fuel [2], etc. Among these, separate addition of fuel can be easily applied to various kinds of fuel (coke or other kind of coal) and numerous experiments for the divided fuel addition process of sintering operation have been attempted [3-7]. But it appears that most of the approach was experimental and field specific, and lacking theoretical analysis under the view of combustion. In the present study, single particle test, sintering pot and sintering field test were performed to investigate effects of different fuel distribution on the coke combustion in the sintering process. In addition, this study presents a single particle combustion model combined with a 1-dimensional bed model of iron ore sintering bed. This model is aimed at providing predictive parameters which can be checked against experimentally measurable quantities.

2. Experimental Approach

2.1 Assembling Pseudo Particles

In the conventional practice of sintering process, coke is added homogeneously into the raw ore mixture to produce pseudo particles.

Inside the pseudo particle, iron ore fines, whose size is typically smaller than that of coke, adhere to coke fines and enwrap them, which would act as a diffusion resistance to the coke combustion. As an improvement, fuel coating method was gradually developed and applied. In this method, fuel portion is coated during the latter part of the granulation process, so that each of the pseudo particles has more fuel element at the outer shell region. By employing alternative fuel distribution method, combustion condition in the sintering process is improved, which is beneficial for increasing productivity, thereby saving energy, while maintaining sinter quality.

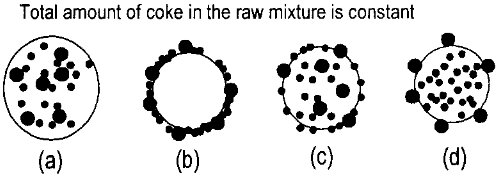


Fig. 2 Intra-particle fuel distribution: (a) Case-Normal, (b) Case-100%LA, (c) Case-50%LA, (d) Case-+1mmLA

Fig. 2 shows various assembling methods of pseudo particles employed in this study. Case-Normal is a case of homogeneous distribution of fuel content in the pseudo particle, as a base case. Case-100%LA and Case-50%LA mean that 100% and 50% of fuel are added in the later stage of granulation. In Case-+1mmLA, fuel particles whose diameter is above 1mm are added in the later stage. In the process of coke late addition, a raw mixture of iron ore, limestone, and selected amount of coke fines was premixed. After the raw mixture was pelletized with water for 150seconds in a rolling drum, coke fines were sprayed in the rolling drum to be mixed with the pelletized raw mixture for additional 90seconds.

2.2 Test Apparatus

For investigation of combustion propagation and its influence on the productivity of sintering process, a single particle test device and a sintering pot test apparatus were used. Fig. 3(a) shows the schematic of the single particle test device, which is composed of isothermal pot, load cell, thermocouples, and air flow tube. The sample in a basket (20mmΦ ×10mm height) is suspended from the load cell. Influent air, of which temperature is set by 1370K, flows into the isothermal pot at a flow rate of 2liter/min. Fig. 3(b) shows one of the sintering pot, which is a batch type pot filled with particles to be sintered, and is exposed to an open flame of gas burner, and combustion gas is transported downward by a suction fan. Test results in a steel pot (200mmΦ, 900mm height) and a transparent pot (108mmΦ, 800mm height) are reported here.

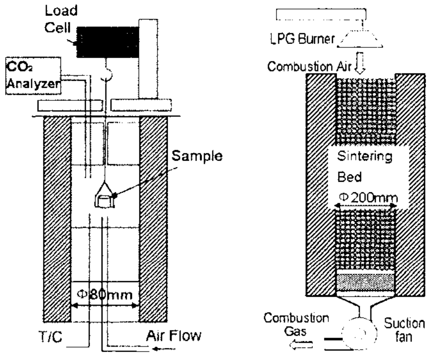


Fig. 3 **Schematic diagram of the experimental devices: (a) single particle test, (b) sintering pot**

The average diameter of coke is 1.7mm, and that of limestone is 1.2mm. The concentration of moisture in the raw mixture is 7% and the density of the raw mixture is set by 1.95g/cm3. After selected amount of pre-processed pseudo particle is fed into the pot, it is exposed to the burner for 90sec and thus ignited. Air flow rate is regulated by setting the pressure difference of the suction fan, which is set at 1,200mmH2O before ignition and at 1,500mmH2O after ignition.

2.3 Test Results

Solid fuel such as coke and/or a selected blend of coal is the energy provider to assure the self-propagation of the heat front through the sinter bed after the ignition. Fuel components of the particles inside the bed are heterogeneously reacting with oxygen from the gas stream through the sinter bed. Kinetics of the reaction itself and/or mass transfer of reacting components can be the limiting factor in the combustion rate [8,9].

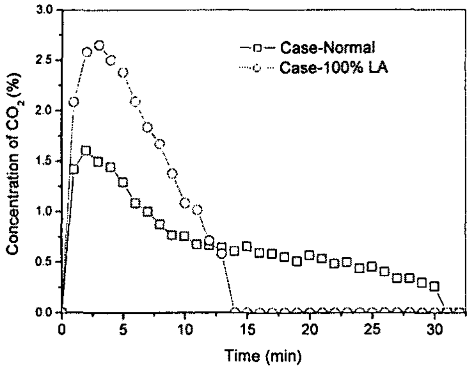
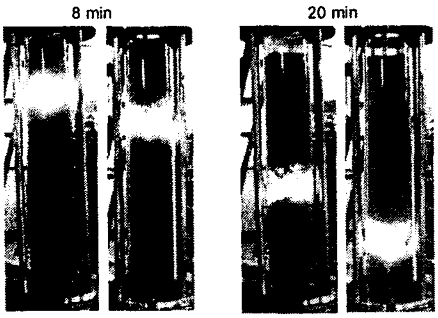


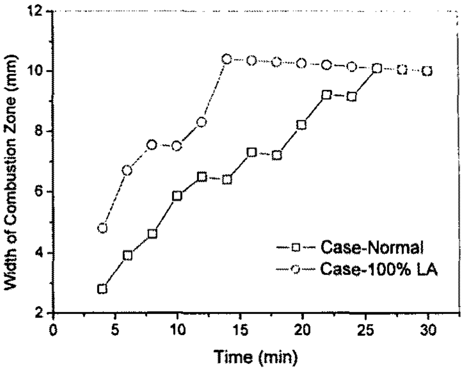
Fig. 4 **Single particle test result: Effluent gas concentration of CO2 for different fuel addition methods**

Experimental investigation for a single solid particle, which was specially prepared to be 13mm in diameter (coke 10% + Fe2O3 90%), was performed for different fuel addition methods. Fig. 4 shows effluent gas concentration of CO2. In the case of late coke addition, CO2 concentration in 0~10min is much higher and falls to zero much faster, which shows that the combustion speed is higher, than in the homogeneously mixed case. This is considered to be feasible because oxygen diffusion is much improved when the fuel element is directly exposed to the stream of oxidizer at the outer surface of the macro particle, compared to the case when the entire fuel component is evenly concealed inside.



Left : Case-Normal
Right : Case-100%LA

(a)



(b)

Fig. 5 **Sintering pot (Pyrex, 108mmD×800mmH) test results of Case-Normal and Case-100%LA:**
(a) Photographs
(b) Combustion zone thickness

Sintering pot tests are designed to simulate the traveling sintering bed, so that combustion characteristics of fuel as well as metallurgical performance of the product are evaluated. Fig. 5 shows the position and thickness of the combustion zone, which can be identified by the bright zone seen through the transparent pot, for Case-Normal and Case-100%LA at 8min and 20min. In Case-100%LA, combustion propagation is faster. Another important observation is the combustion zone thickness, as summarized in Fig. 5(b). During the initial stage, combustion zone in the Case-100%LA is thicker than in the Case-Normal, and after 15min, the thickness is maintained constant for the Case-100%LA, while the thickness in the Case-Normal is still increasing. In Case-100%LA, coke combustion rate is fast, and combustion time for each particle is short. That causes thicker combustion zone than in the Case-Normal during the earlier stage of the process, i.e. in the upper part of the bed, and prevents accumulation of heat in the later stage of the process, i.e. in the lower part of the bed. In Fig. 5(a), a dispersed flame zone is observed in the Case-Normal at 20 min, which shows longer combustion time. This is not observed in the upper part of the bed, since air supplied in the trailing edge of the flame zone is not hot enough to maintain the coke combustion. Thicker combustion zone in the upper part of the bed is favorable because iron ore fines are supplied with more energy for sintering. These results demonstrate that combustion characteristics of macro particles and their fuel component are crucial to the propagation of the combustion zone and its thickness, which would determine productivity of the whole process as defined in Eq. (1).

Fig. 6 shows sintering time and productivity for the 4 cases of fuel distribution. As late addition of coke is increased, sintering time is decreased, which means combustion propagation within the bed becomes faster. This result is consistent with the observation from the transparent pot tests that combustion rate is increased as more fuel is distributed at the outer shell of the particle, resulting from the enhancement of oxygen diffusion. However, as for the results of productivity, it can be seen that in the case of coke late addition, the product yield declines. The reason might be that in the case of coke late addition, the coke fines of smaller size, whose combustion speed is faster, could not supply sufficient amount of heat for melting of the iron ore mixture in the inner layer of the macro particle. In other words, the coke component of smaller size is burning out quickly, and the propagation speed of the apparent flame zone is faster, but amount of generated heat is not sufficient enough for the melting of the iron ore mixture.

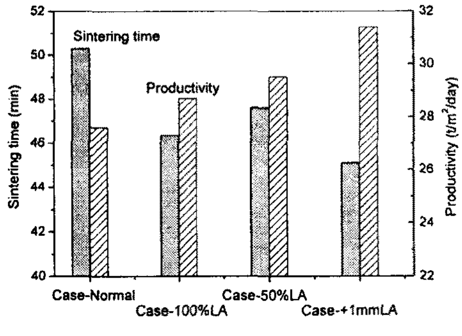


Fig. 6 Test results of steel pot test (200mmD×900mmH)

Another explanation is that when all coke particles are added outside, thermal penetration into the core would become worse. That problem can be overcome a bit by 50% coke late addition (50% LA), in which case sintering time is shorter than in Case-Normal, and better productivity than those of Case-Normal and Case-50%LA is observed. However, in Case-+1mmLA, both productivity and sintering time are significantly improved, compared to the Case-100%LA and Case-50%LA. This result demonstrates that quality of the product of Case-+1mmLA is better than that of Case-50%LA. Since the size of fuel element located on the surface is larger, then the surface area for char combustion is smaller for the Case-+1mmLA, combustion time for a single pseudo particle is longer than that in the Case-100%LA. Therefore, duration time of iron ores in the high temperature is increased in that case, which results in the improvement of the product strength. It can be seen that the combustion pattern of a single pseudo particle should be carefully controlled for maximum productivity of the sintering bed. That can be achieved by controlling the size of fuel fines and by applying the fuel late-addition method, i.e. by modifying the intra-particle fuel distribution pattern.

3. Numerical Approach and Results

Although it is important to know the factors which influence the sintering performance and the relation between the factors, sintering process is poorly understood on a mechanistic level [10]. Numerical modeling is capable of augmenting the information obtained from the laboratory and plant trials.

An essential simplification in previous numerical investigations in iron ore sintering processes [10-14] was the assumption of homogeneity inside a particle where only the surface reaction on a particle is considered, which means that there is no temperature and species concentration gradient inside a single particle. However, especially in the case of particularly that of coke combustion. Granule surface temperatures, which affect convective heat transfer rates, may deviate considerably from the mean granule temperature assumed [10].

Different from the previously proposed particle model where the particle was composed of a single homogeneous solid phase, a single particle model is proposed to describe the combustion process inside the individual pseudo particle. This model study is intended to provide more information on individual particles, while maintaining relevancy with the entire bed of fuel particles. A bed model for iron ore sintering process has been proposed by authors [14], along with discussions on previous models [10-13] and applications in incinerators [15] or gasifiers [16].

Single particle model has a form of unsteady and 1-dimensional partial differential equations for a spherical particle and is composed of oxygen diffusion equation, mass, energy, and component conservation equations for the solid phase. Oxygen concentration is a function of time and radius, and depends on the diffusive flux and chemical reaction:

$$\frac{\partial(fC_{O_2})}{\partial t}=\frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 fD_{eff,O_2}\frac{\partial C_{O_2}}{\partial r}\right]+\dot{\omega}_{O_2} \qquad (2)$$

Where f is particle porosity, C_{O_2} is oxygen concentration, is effective diffusion coefficient of oxygen considering the porosity and the influence of tortuosity on the diffusion, is the oxygen consumption rate by combustion with char. For the solid phase, conservation equations are described as following,

Mass : $$\frac{\partial(\varepsilon\rho_s)}{\partial t}=\sum_{r_s}\dot{M}_{s,r_s} \qquad (3)$$

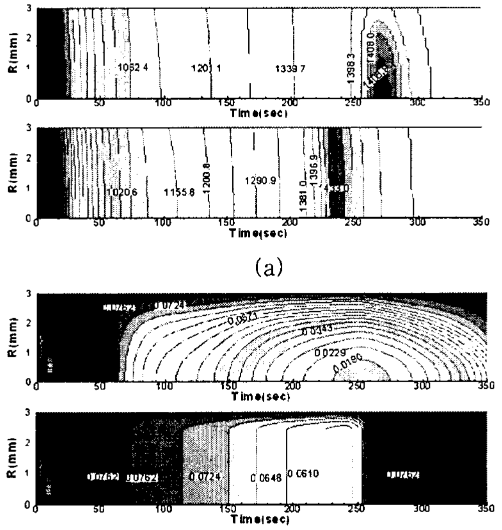
Energy:

$$\frac{\partial(\varepsilon\rho_s C_{p,s}T_s)}{\partial t}=\frac{1}{r^2}\frac{\partial}{\partial r}\left(\varepsilon r^2\lambda_s\frac{\partial T_s}{\partial t}\right)+\sum_{r_s}y\dot{M}_{s,r_s}\Delta H_r-\left(\sum_{r_s}\dot{M}_{s,r_s}\right)C_P T_S$$

(4)

Component : $$\frac{\partial(\varepsilon\rho_s m_{s,k})}{\partial t}=\sum_{r_s}\dot{M}_{s,k,r_s} \qquad (5)$$

where ε is volume fraction of the solid in the particle, ρs is overall density of the particle, is mass loss rate per unit volume for the solid phase through reactions, rs is reaction number, Ts is local temperature of the solid phase, Cp,s is overall heat capacity of the solid, and λs is overall heat conductivity. Heat of reaction is ΔHr. The second term on the right-hand side of Eq. (4) is reaction heat absorbed by the solid where y is the fraction of reaction heat absorbed by the solid. The third term of Eq. (4) is sensible heat loss of evolved gas. ms,k is the mass fraction of the solid component k. $\dot{M}_{s,k,r_s}$ is loss rate per unit volume for the k component of the solid phase through reactions. Source term of each controlling equation is closely combined through the interaction between phases.



(a)

(b)

Fig. 7 Simulation results from a single particle combustion model for Case-Normal (the upper part) and Case-100%LA (the lower part): (a) Temperature, (b) Oxygen concentration

Fig. 7 shows one of the temperature and oxygen concentration distributions obtained from the simulation of a single pseudo particle for the Case-Normal and Case-100%LA. Diameter of the pseudo particle is 6 mm and initial mass fraction of coke is 4%. The pseudo particle is exposed to air flow whose velocity is 0.4 m/s and whose temperature is 1373K. The results demonstrate that the temperature gradient inside the particle is not obvious, but the oxygen concentration gradient inside the particle is significant.

It can be concluded that oxygen diffusion process inside a pseudo particle is different from that of a separate coke particle. So it is reasonable to take a correction factor to the overall fuel combustion rate for various fuel distribution methods. The correction factor for coke combustion rate can be determined *according to the coke combustion time.* Here, based on the coke combustion rate value of the normal coke addition, the coke combustion rate RC of coke late addition can be expressed as

$$R_C = \frac{A_s v_s W_{coke} C_g}{\frac{1}{k_r} + \frac{1}{k_{ml}}}, \qquad \text{where } k_{ml} = \xi k_m \qquad (6)$$

Where As is surface area, vs is stoichiometric coefficient, Wcoke is molecular weight of coke, Cg is molar concentration of reactant gas, kr is Arrhenius reaction rate, and kml is mass transfer coeffcient related to diffusion in the particle layer. Considering the coke combustion time of Case-Normal (~250min)and Case-100%LA (~350min) obtained from the calculation of the single particle model, the correction factor ξ for the coke combustion rate of coke late addition is taken as 1.4 for Case-100%LA.

This effect of intra-particle fuel distribution as seen from the single particle combustion model is further extended to the simulation using a bed combustion model. Fig. 8 shows results of temperature distribution within the sintering bed for the cases of fuel distribution: Case-Normal and Case-100%LA. Bed configuration is selected to simulate an actual sintering facility. The bed of 570 mm height is exposed to hot gas of 1400 K temperature for 90 seconds for ignition. Conditions of pseudo particles are identical to those used in the calculation of single particle model. For Case-Normal, flame front reaches the point of y=100mm at t=1040s, while for Case-100%LA, the flame front reaches the point of y=100mm at t=950s. Thus, for Case-100%LA, the front of the combustion zone reaches the bottom more quickly; i.e., the propagation of combustion is faster. The difference of total sintering times between the two cases is: (1040-950)/1040=8.6%.

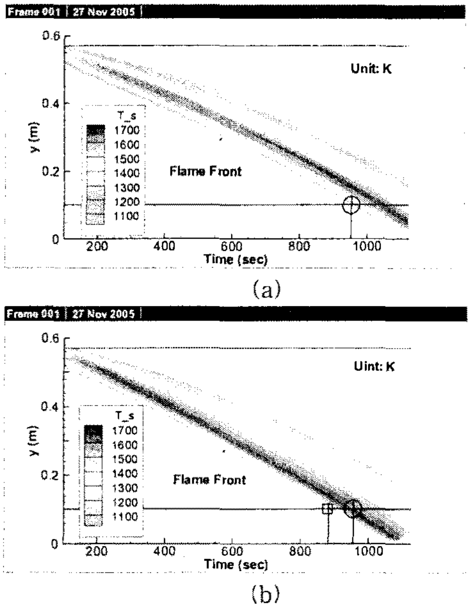


Fig. 8 **Temperature distribution from 1-dimensional bed model (Bed height 570mm): (a) Case-Normal (b) Case-100%LA**

Since the height of the sintering pot used in the numerical study is less than that of experiment pot(570mm : 900mm), the decrease of sintering time is also less than that of experiment pot(8.6% : 14.8%). This result shows evidently that the difference of oxygen diffusion within the single pseudo particle can affect the whole sintering process.

4. Conclusion

Effects of fuel distribution in the pseudo particle on the whole sintering process were investigated by experimental and numerical approach. This study was aimed at finding out the optimum palletizing method for improving productivity of the sintering process, while maintaining the strength of the sintered product. The results of single particle tests and sintering pot tests show that combustion speed of coke late addition is faster than that of normal and even distribution. Sintering pot tests show that the productivity in the case of coke late addition is higher than that in the case of normal distribution. Further, 50% coke late addition and +1mm coke late addition can improve the product yield and the strength, which was discussed with the effect of the thickness of the combustion zone. From these results, it can be seen that distribution method of fuel of large particle size as well as combustion rate of a single pseudo particle play a crucial role in the productivity through the combustion propagation and the combustion zone thickness within the sintering bed. A single particle model is proposed for pseudo particles which may have different distribution of fuel inside. This model enables to check the effect of temperature and species gradient inside the particle. Combining the single particle model along with a bed combustion model, simulation results for a sintering plant are shown to reflect the effect of different methods of fuel addition. The simulation results are supported by experimental results of sintering pot and sintering field test.

Acknowledgement

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