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Numerical Modelling of Temperature Distribution and Pressure Drop through the Layered Burden Loading in a Blast Furnace

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ABSTRACT

Analysis of the internal state of the blast furnace is necessary to predict and to control the operating conditions. Especially, it is important to develop models of the blast furnace to predict the cohesive zone because shape of the cohesive zone influences overall operating conditions of blast furnace such as gas flow, chemical reactions and temperature. Because many previous blast furnace models have assumed cohesive zone to be fixed, it was not possible to evaluate the shape change of cohesive zone in relation with operating conditions such as PCR, blast condition, and production rate. In this study, an axi-symmetric 2-dimensional steady state model is proposed to simulate blast furnace processes. In this model, cohesive zone is determined by the solid temperature. Finite volume method is employed for numerical simulation. To find location of the cohesive zone, entire calculation procedure is iterated until converged. Through this approach, shape of the cohesive zone, velocity and temperature within the furnace are predicted from the model.

Key Words : Blast furnace, Numerical model, FVM, Cohesive zone

기 호 설 명

Alphabets

A : Surface area, m^2/m^3
C_p : Specific heat, J/kg · K
dp : Particle diameter, m
G : Mass flow rate, $kg/m^2 \cdot s$
h : Heat transfer coefficient between gas and solid phase, $W/m^2 \cdot K$
k : Thermal conductivity, W/m · K
P : Gas pressure, Pa
Re : Reynolds number
Pr : Prantdl number
T : Temperature, K

Greeks

μ : Viscosity, $N \cdot s/m^2$
ε : Porosity
ρ : Density, kg/m^3
ϕ : Shape factor
ψ : Potential function

Subscripts

g : Gas phase
s : Solid phase
i : Ore or coke, gas and solid phase
j : Species of each phase
gs : Between gas and solid

1. Introduction

Blast furnace process is applied to produce liquid pig iron which is suitable for subsequent refining to steel. Fig. 1 shows the blast furnace processes. Blast furnace is a tall, vertical shaft furnace in which iron ore is reduced into pig iron. Iron ore, coke and flux including limestone and dolomite are charged into the top of the furnace. Hot air and oxygen (~1100℃) are supplied through the tuyere and descending coke and pulverized coal supplied through tuyere in raceway are burning. Reducing gases such as CO and H_2, generated as a result of combustion in the raceway, heat up the charging material. And iron ore is reduced and melt by the reducing gases. Molten pig iron and slag are discharged through the tap hole near the bottom of the furnace. Internal of blast furnace is classified into 5 zones; stack zone, cohesive zone, dripping zone, raceway and deadman depending on the phenomena occurred in the furnace as shown Fig. 1 Particularly,

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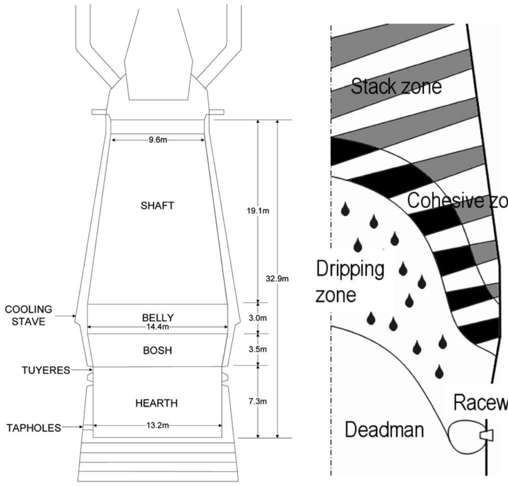


Fig. 1. Blast furnace processes.

gas permeability is greatly reduced at the cohesive zone due to agglomeration and melting of the iron ore. Accordingly, cohesive zone has a close connection with the thermal efficiency, permeability and reducibility of the furnace. Therefore, it is necessary to predict the shape of the cohesive zone and evaluate the effects of the cohesive zone in the blast furnace process. Some model studies have been previously carried out for prediction of the blast furnace process. Yagi et al. established a two-dimensional steady state model which considered four phases such as solid, gas, liquid and particle[1-3]. And BRIGHT model considers a charging the distribution model and the forecasted distribution of the burden as well as temperature distribution of the burden and chemical composition of the gas [4]. Recently, three-dimensional steady state model[5] and two-dimensional unsteady state model[6] have been also developed. A mathematical model was developed to estimate the gas flow and temperature distribution according to the size of the raceway depth when the profile of the cohesive zone was assumed by Jeong et al[7]. Objective of this study is to present a steady two-dimensional model for predicting the shape of the cohesive zone and to predict the operating conditions such as pressure and temperature in the blast furnace using a numerical model. And the numerical model is verified by comparing the calculated results with measurement data.

2. Mathematical Model

A steady state axi-symmetric two-dimensional model is considered in this study, which considers only two phase of solid and gas phases. Components of gas and solid phase are listed in Table 1. Ore consists of hematite (Fe_2O_3) and coke, carbon. Other components like ash and gangue are not considered in this study.

Table 1. Species of gas and solid

Phase	Gas	Solid
Species	CO	Ore(Fe_2O_3)
	CO_2	Coke(C)
	H_2	
	H_2O	
	N_2	

Main assumptions are shown as below,

(1) Ergun's equation is applied to describe the gas flow. Gas production and loss by reactions are ignored because the amount of gas in reaction is very small compared with the blast through the tuyere.

(2) Solid velocity is assumed to be proportional to the gradient of the velocity potential.

(3) Phenomena in the raceway are not considered in the model. Adiabatic flame temperature and gas compositions, calculated by heat and mass balance, are applied to boundary conditions at the raceway.

(4) Deadman shape is assumed as a polynomial.

(5) Layer structure of coke and ore is assumed to be fixed.

(6) It is assumed that coke and ore diameter are function of location only. Because this model can't consider the change in diameter by reaction, particle diameter in each zone is assumed to be fixed.

(7) Shape of the cohesive zone is defined by ranging temperature distribution

2.1. Governing Equation

To describe the gas flow in the furnace, Ergun's equation, extended to 2D, is adopted and expressed as below,

$$-\nabla P = (f_1 + f_2 |\vec{G}_g|)\vec{G}_g \tag{1}$$

where, $f_1 = 150 \dfrac{(1-\varepsilon_i)^2 \mu}{(\phi_i dp_i)^2 \varepsilon_i^3 \rho_g}$, $f_2 = 1.75 \dfrac{(1-\varepsilon_i)}{\phi_i dp_i \varepsilon_i^3 \rho_g}$

Solid flow is assumed to be potential flow. It can be expressed as below,

$$-\nabla \psi = \vec{G}_S \tag{2}$$

$$\nabla \cdot \left(-\nabla \psi\right) = \nabla \cdot \vec{G}s = 0 \tag{3}$$

Energy conservation equations for gas and solid can be constructed in a general form of partial differential equations and expressed as below,

$$\nabla \cdot \left(\vec{G}_g C_{pg} T_g - k_g \nabla T_g\right) = h_{gs} A_{gs} \left(T_g - T_s\right) \tag{3}$$

$$\nabla \cdot \left(\vec{G}_s C_{ps} T_s - k_s \nabla T_s\right) = h_{gs} A_{gs} \left(T_g - T_s\right) \tag{4}$$

2.2. Boundary Conditions

Boundary conditions of the raceway are applied for all governing equations except the gas flow. All oxygen and hydrogen, included in air, enriched oxygen and moisture, react with carbon and are transformed into CO and H_2 respectively. And because enthalpy is conserved, adiabatic temperature is calculated from a simple heat balance. This temperature is adopted as boundary condition at the raceway for gas temperature[8]. For gas flow, mass flow rate of gas is given as boundary condition and top pressure is used for the exit condition. Temperature of gas and solid at inlet, tuyere and furnace top, respectively, are given as fixed value and at outlet heat flux by diffusion is set as zero, and heat loss due to the cooling stave of the wall is considered. At this time, wall temperature is 300K. In the axis, gradients of all scalar values are zero by axi-symmetric conditions.

2.3. Heat Transfer Between Gas and Solid

Heat transfer coefficient between the gas and the solid can be calculated using the Ranz-Marshall equation.

$$h_{gs} = \frac{k_g}{d_s}\left(2.0 + 0.6\,\mathrm{Re}_{gs}^{1/2}\,\mathrm{Pr}_g^{1/3}\right) \tag{5}$$

Heat transfer area is expressed as blow,

$$A_{gs} = \frac{6(1-\varepsilon_i)}{dp_i \phi_i} \tag{6}$$

2.4. Physical properties

ore and coke densities are 3500 and 1000 kg/m^3. Gas viscosity and thermal conductivity are calculated by Wilke's method[9]. Heat capacity of a species is a function of temperature and the one of each phase calculated by summation of mass fractions multiplied by capacity of its species.

Heat capacity of each species in gas phase :

$$C_{p,j}(T_i) = a_j + b_j T_i + C_j T_i^2 \tag{7}$$

Heat capacity of each species in solid phase :

$$C_{p,j}(T_i) = a_j + b_j T_i + C_j / T_i^2 \tag{8}$$

Heat capacity coefficients are from literature[10].

2.4. Solution Procedure

Fig. 1 shows the geometry and the size of the blast furnace used for calculation. Height of the furnace is 32.9 m, radius of the hearth is 6.7 m, height of the bosh is 4.8 m and radius of the belly is 7.2 m. Figure 2 shows the grid structure and the initial layer structure. Raceway is assumed to be 1.0 m high and 1.5 m wide. 1235 node points and 1152 elements are employed for the numerical analysis as shown in Fig. 2. In the stack zone, grid structure is determined according to the layer structure. At the initial point, whole regions except deadman and raceway are assumed as stack zone, in which coke and ore are piled up alternately. In central column of furnace (~0.8 m from axis), only coke is charged, which helps gas flows well. It is because that diameter of coke is lager than that of ore. solution procedure is also shown in Fig. 2. Finite volume

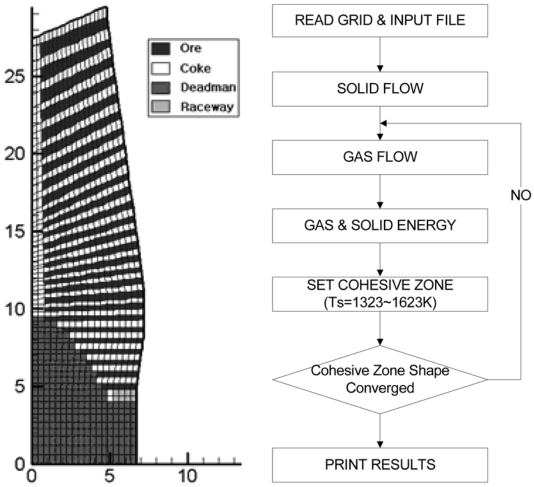


Fig. 2. Initial layer structure and solution procedure.

method is employed to solve governing equation and staggered grid is used for solving flow. Shape of cohesive zone is defined by ranging from 1050~1350℃, and all calculation procedure is iterated until shape of cohesive zone is converged.

3. Results and Discussions

Table 2 shows operating parameters of 3 cases. Case A indicate usual operation, case B indicates the high PCR (pulverized coal rate) operation and case C indicates the high productivity operation. Ordinary productivity of the furnace is about 9000 ton/day. In the high PCR operation, more amount of pulverized coal (PC) and less amount of coke are used because a part of coke is replaced by PC owing to economic reasons. But total amount of coke and PC is not changed. In high productivity operation, productivity is 800 ton/day higher than other operations. Therefore, amount of supplied raw material is increased.

Boundary conditions of the raceway are calculated based on these operational conditions. These results are shown in Table 3, which shows that the temperature at the raceway in high PCR operation is lowest. It is because temperature of the supplied PC is about 300K, while that of coke descending toward the raceway is 1800K. Therefore energy of combustion is utilized to raise the temperature of PC. In high PCR operation, CO mole fraction is larger than that in the case of usual operation due to the difference of amount of blowing air and oxygen.

Table 2. Operating condition for blast furnace

	A	B	C
Top gas pressure (MPa)	0.277	0.265	0.277
Blast volume (Nm^3/min)	6150	6166	6312
Blast pressure (MPa)	0.4192	0.4187	0.4206
Blast temperature (℃)	1191	1174	1201
Production rate of pig iron (t/d)	9284	9218	10129
PCR (kg/t-pig)	147.6	226.3	159.9
O_2 rate (Nm^3/hr)	20000	21213	26551
Blast moisture (g/Nm^3)	22.3	19.2	8.4
Coke rate (kg/t-pig)	341.6	258.9	327.5
Ore rate (kg/t-pig)	1683	1640	1588

Table 3. Boundary conditions in raceway

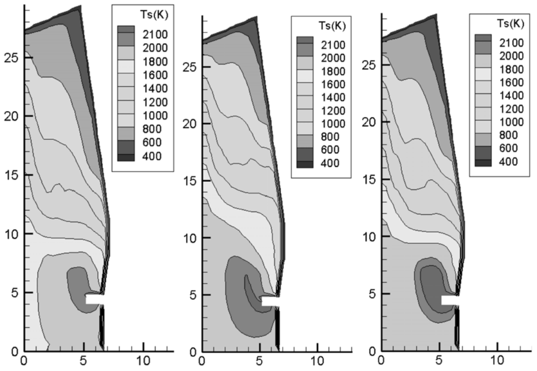
Case	T_F(K)	Mole fraction		
		CO	H_2	N_2
A	2410.6	0.411	0.022	0.567
B	2308.6	0.413	0.019	0.568
C	2515.6	0.423	0.008	0.568

Table 4. Layer properties

Layer		Dp (mm)	ϕ (-)	ε (-)
Coke	Central column	50.0	0.90	0.45
	Stack zone	50.0	0.90	0.43
	Dripping zone	25.0	0.90	0.43
	Deadman	25.0	0.90	0.20
	Raceway	25.0	0.90	0.80
Ore	Cohesive zone	19.1	0.84	0.10
	Stack zone	19.1	0.84	0.36
	Near-wall	10.0	0.84	0.36

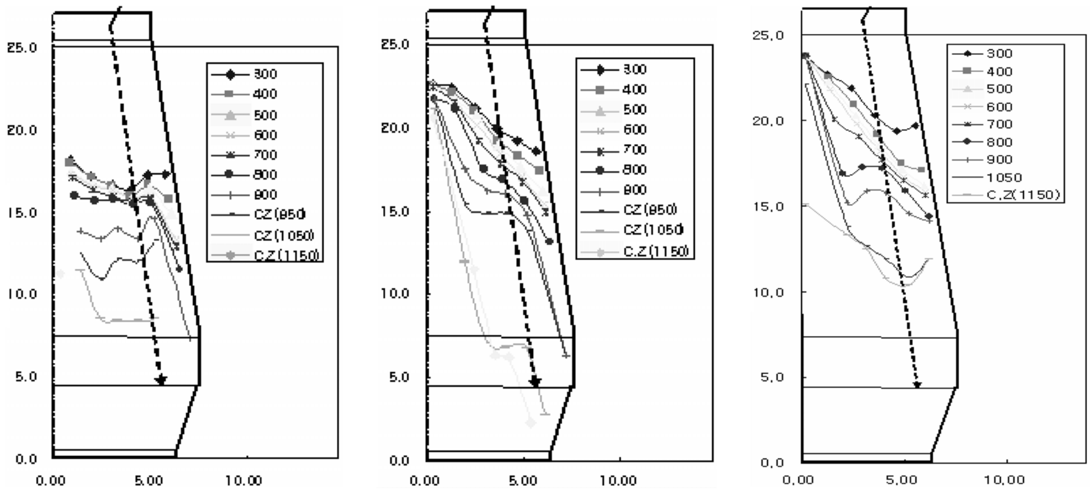
Table 4 shows the layer properties such as particle diameter, shape factor and porosity. In the central column, only coke is charged as described before. Initial diameter of coke and ore charged into the top of furnace, is 50 mm and 19.1 mm, respectively. As coke goes down, diameter of coke is decreasing as a result of reaction. Therefore, diameter of coke below the cohesive zone is set as 25 mm, which is half of the initial diameter. Porosity of the cohesive zone is set as 0.10 to reflect the low permeability due to agglomeration. Porosity is increased to 0.80 in the raceway.

Fig. 3 shows the simulation results of temperature distribution within the blast furnace for the cases of usual, high PCR and high productivity operation. For the case of high PCR and high productivity operation, temperature is higher than in the usual operation case. Because the amount of coke rate charged into the furnace top for the case of high PCR operation is smaller than the amount in usual operation case, solid



(a) Usual (b) High PCR (c) High Productivity

Fig. 3. Simulated temperature distribution.



(a) Usual (b) High PCR (c) High Productivity

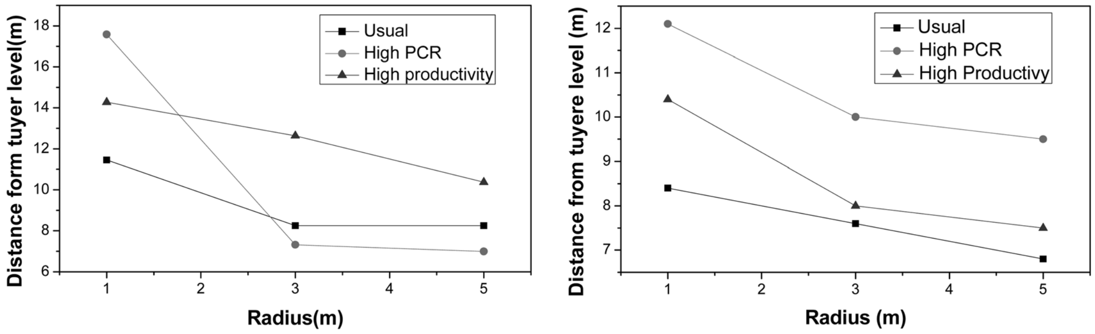
Fig. 4. Measured Temperature distribution.

mass flow rate is reduced and residence time is increased. For that reason, a rise in temperature is larger.

Fig. 4 shows the temperature distribution measured by 6 points descending probes in the actual furnace. For all cases, there is a thick thermal conservation zone (950~1050℃) above the cohesive zone. Temperature above 1150℃ could not be measured because of the thermocouple's ability. For the case of usual operation, temperature within the furnace is lower than in other cases. Simulation results show the same trend with the measurement results.

Fig. 5 shows the height of the cohesive zone (Ts= 1050℃) from the tuyere level at points of 1.0, 3.0 and 5.0 m with radial direction for 3 operating conditions. Cohesive zone is high following the order of high PCR, high productivity and usual operation in the side of the central region, but in the order of high productivity, high PCR and usual operation in side of wall, which implies that in high PCR operation, temperature is changed rapidly along the radius and shows a different tendency with the simulated result. In high PCR operation, amount of coke charged into the furnace is smaller than that of usual operation, which means coke layer thickness is reduced in the stack. Therefore, it affects operating conditions such as gas flow through the coke layer, heat transfer and chemical reaction. Because the layer structure is fixed regardless of the operating conditions, this model has a limitation that it can not accommodate the change of the layer structure.

Fig. 6 shows the gas pressure change according to the height. Major portion of the pressure drop is occurred in the cohesive zone (1050~1350℃), which has low permeability. In other zones except the cohesive zone, pressure drop is occurred slowly.



(a) Measured results (b) Calculated results

Fig. 5. Distance from tuyere level of CZ (Ts=1050°C).

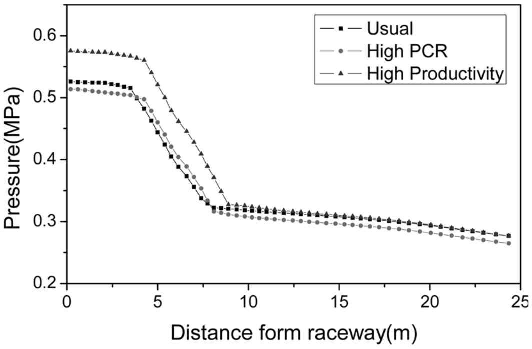


Fig. 6. Gas pressure along height in the axis.

4. Conclusions

Numerical investigation was performed to predict the shape of the cohesive zone in the blast furnace. The model includes heat transfer between gas and solid and layered burden structure of coke and ore. Simulation was conducted for the cases of usual, high PCR and high conductivity. Finite volume method was employed for analysing the temperature distribution and the shape of the cohesive zone. Validity has been examined comparing to the model predictions and the measurement data. Because the layer structure is fixed regardless of the operating conditions, this model has a limitation that the model can not accommodate the change of the layer structure and chemical reaction. Despite of these limitations, it serves as a stepping stone toward the development of a more comprehensive model which would include chemical reactions and its associated heat transfer.

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