Numerical Analysis of Static Holdup of Fine Particles in Blast Furnace

Sungging PINTOWANTORO, Hiroshi NOGAMI and Jun-ichiro YAGI

Institute of Multidisciplinary Research for Advanced Materials, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai 980-8577 Japan. E-mail: yagi@tagen.tohoku.ac.jp

(Received on June 12, 2003; accepted in final form on September 10, 2003)

With increased in pulverized coal injection rate into blast furnace, the importance of understanding flow characteristics of powders within packed bed increases because more unburned char and coke fragments would be generated, it would be deteriorate permeability in the blast furnace. Although flow characteristics of dynamic or total holdup of powders in packed beds is found in several reports,^{3–6)} behavior of powders in blast furnace using separate treatment of dynamic and static holdup has yet to be reported. In this study the behavior of static powders was examined through numerical simulation using the “four fluid model”,³⁾ which included the formulation of static powders behavior. The model results were compared with two dimensional temperature distributions measured in the furnace for three different pulverized coal injections (PCI) rates (100, 200 and 250 kg/thm) for validated. The model was applied to quantitative analysis of static powders holdup in the blast furnace operation with high-rate pulverized coal injection. The higher amount of static powders holdup was found mostly in the center lower deadman, above and below the tuyere level, and in upper shaft, for PCI rate 100 kg/thm, 150 kg/thm, 200 kg/thm and 225 kg/thm respectively. The lower amount of static powders holdup was found in the raceway region throughout the surface of deadman.

KEY WORDS: blast furnace; mathematical modeling; multi-phase flow; pulverized coal injection; chemical reactions; static powders holdup.

1. Introduction

The production of pig iron in the blast furnace is the major route among various iron making processes. In recent years, the blast furnace processes have been undergoing refinements to improve productivity, reduce operating costs, and extend coke oven life and to lower the greenhouse effect of gas. In order to improve the economy of the blast furnace process, injection of large amounts of reductant, like pulverized coal, oil or natural gas through the tuyere has become more widely used and can be an attractive technology in blast furnace process.¹⁾

Basically, there are two factors that limit the rate of reductant injection through the blast furnace tuyere.²⁾ The first factor is due to the permeability of gas or liquid reason. A certain coke rate is necessary, because it can provides permeability (in the dry as well as the wet zones) and mechanical support to the large charge column, thus permitting gases and liquid passing through the void. The minimum coke rate for a proper blast furnace operation depends on several different factors, among which the quality of coke and ferrous burden, together with the burden distribution. As these materials descend within the furnace, the physical and chemical change occurs, which also includes reduction, shrinkage, meltdown and combustion. The second factor is for combustion of pulverized coal in the raceway. While the pulverized coal injected increases, the com-

bustibility of pulverized coal decreases due to decrease of excess air ratio, and caused an increase in unburned pulverized coal flows from the raceway then further react with slag, gas and hot metal somewhere in the furnace. Although their reactivity is much higher than that of coke, much of unburned pulverized coal are consumed by in-furnace reactions (direct reduction, solution loss, coke silica reduction, melting/slag, water gas reaction and carbon dissolution). However, if the amount of unburned pulverized coal particles inside the blast furnace is higher than what can be consumed by such reactions, a significant amount of unburned pulverized coal could be accumulated, causing severe operational problems, such as reduced the gas and liquid permeability, an undesirable gas and temperature distribution, and possible hanging of the burden.

In order to overcome these problems, it is important to clarify the flow characteristics and holdup behavior of unburned char for the achievement of high pulverized coal injection (PCI) rate and the stable operation of the blast furnace. Understanding the distribution of powders in furnace, specifically for static powders holdup, is important because it leads to the development of new furnace control technique.

Although flow characteristics of dynamic or total holdup of powders in a blast furnace is found in several reports,^{3–5)} the behavior of powders in blast furnace using separate treatment of dynamic and static holdup has yet to be report-

ed.

Therefore, this work is to extend the behavior of powders phase with consider dynamic and static holdup. It would be examined through numerical simulation using the “four fluid model” in blast furnace operation with increase in pulverized coal injection rate. The model considers explicitly six phases namely gas, solid, hot metal, slag, dynamic powders and static powders. A numerical analysis of static powders holdup in a blast furnace can be clarified.

2. Mathematical Model

2.1. Generalized Conservation Equation

The mathematical model used in this study is two dimensional, steady state and axisymmetric. It consists of conservation of mass, momentum, enthalpy and chemical species of gas, solid, hot metal, slag, dynamic powders and static powders phases. The static powders phase is newly introduced phase in the present model. The governing general conservation equations for all phases are represented by the following equation.

$$\frac{\partial}{\partial x}(\epsilon_i \rho_i u_i \psi) + \frac{1}{r} \frac{\partial}{\partial r}(r \epsilon_i \rho_i v_i \psi) = \frac{\partial}{\partial x} \left(\epsilon_i \Gamma_\psi \frac{\partial \zeta}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(r \epsilon_i \Gamma_\psi \frac{\partial \zeta}{\partial r} \right) + S_\psi \dots (1)$$

Where the subscript i stands for the different phases being considered. S_ψ is source term, whereby the continuity and species equations have mass sources due to chemical reactions and phase transformations. When the diffusive variable is not equal with general dependent variable, the diffusive term become a source term and combined with S_ψ . Especially, when general dependent variable is equal with the enthalpy for phase i , the diffusive variable equal with the temperature of phase i and likewise the conductive heat transfer terms become a source term. The conservation of mass, momentum, enthalpy and species represented by changing ψ in Eq. (1), it is used to solve the conservation equations simultaneously by using a control volume formulation. New or modified features of the model are discussed below.

2.2. Formulation of Static Powders Holdup

Fundamental behavior of powders deposition within packed bed particles is shown in **Fig. 1**. After unburned pulverized coal leaves the raceway it could be assimilated by the various phases including the solid particle, hot metal, gas and the slag phase. The unburned pulverized coal in the gas stream, known as dynamic powders, passed through the voids and deposited onto the surface and/or trapped in the dead space between solid particles it become static, thus known as the static powders. Though it becomes static powders, they can still detach itself and joined to the gas stream again. Therefore, the net rates of powder deposition depend on both the adhering rate of powders to the surface of particles and their departing rate to the gas stream.

In the foregoing calculations, all powder holdup has been assumed to be dynamic holdup. That is, all powders are treated as constantly flowing. However, static powder

Fig. 1. Flow model of fine powders.

holdup does exist in the blast furnace. Physical properties of static powder holdup, depend on the localized condition (diameter, shape, density) and also chemical reaction of powders and other phases, particularly gas and packed solids.

Generally, correlation on static powder holdup can only be derived from experiments.⁶⁾ In this model static powder holdup would be included in the general conservation equation as it contributes to the transport properties of all phase. The word “static” implies that the fine powder is not moving against the packed solid. The packed solid however is actually moving slowly. A static powder holdup thus appears in extra convective transport term which used the solid velocity field instead of the phase velocity field of static powder. This is due to the static holdup of powder sticking to the surface of solid particle and/or is in space among solid particles. The modified form of Eq. (1), the distribution of volume fraction of static powders holdup related with deposition rate of powders can be written as follow.

$$\frac{\partial}{\partial x}(\epsilon_{fs} \rho_{fs} u_s) + \frac{1}{r} \frac{\partial}{\partial r}(r \epsilon_{fs} \rho_{fs} v_s) = R_f \dots (2)$$

R_f is the net deposition rate of powders. This rate is expressed by the difference between adhering rate (r_s) and departing rate of powders (r_d). Hidaka *et al.*⁶⁾ used Eq. (3) below to evaluate the deposition rate of powders.

$$R_f = r_s - r_d = \rho_f (k_f a \epsilon_f - k_r a \epsilon_{fs}) \dots (3)$$

Where

$$k_f a = 1/400 \{1 + 10(G_g/G_f)^{-3.0}\} d_f^{1/2} \dots (4)$$

$$k_r a = k_r a (\epsilon_{f0}/\epsilon_{fs0}) \dots (5)$$

The dynamic powder holdup is calculated by the following empirical equation.

$$\epsilon_{f0} = \frac{1}{\rho_f} \left(\frac{G_f}{G_f + G_g} \right)^{1.25} \times \left[200 \exp \left\{ -1.25 \left(\frac{u_g - u_z}{\left(\frac{G_f}{G_f + G_g} \right)} \right) \right\} + 480 d_f^{1/3} \right] \dots (6)$$

The parameters in Eq. (6) are determined as follows:

$$G_f = \rho_f u_f \varepsilon_f; \quad G_g = \rho_g u_g \varepsilon_g; \quad u_z = 0.275 \left(\frac{\rho_g d_f v_{tf}}{\mu_g} \right)^{0.15}$$

The static powder holdup calculated with the following empirical equation.

$$\varepsilon_{fs0} = 0.007 (\varepsilon_g u_g)^{-1.5} G_f^{0.2} \dots \dots \dots (7)$$

To solve the equations of motion, special mention is introduced for the formulation. The gas and solid phases are treated as continuous phases and hot metal, slag, static and dynamic powders are discontinuous phases. Interaction between dynamic powders and liquid phases has not yet been considered. The continuity equation is used to calculate the phase volume fraction distribution. To determine the gas volume fraction Eq. (8) is used, where the volume fraction of lump solids can be obtained from empirical correlation for iron and coke.

$$\varepsilon_g + \varepsilon_s + \varepsilon_{hm} + \varepsilon_{sl} + \varepsilon_f + \varepsilon_{fs} = 1 \dots \dots \dots (8)$$

2.3. Boundary Condition

To solve the above equations, Eqs. (2)–(8), it is necessary to specify appropriate boundary conditions applied to the blast furnace mathematical model. The mass inflow rates, temperatures and compositions for the gas and dynamic powder are specified at the tuyere. Along the furnace wall, the solid uses a free slip velocity boundary condition in the upper shaft, and wall friction factors in the bosh are used. The gas phase velocity is free slip along the entire wall except at the tuyere. Both gas and solid lose heat to the wall due to wall cooling.

At the burden surface, the solid temperature, composition and distributions of component diameters and volume fractions are specified. The solid inflow rate and velocity distribution are calculated as part of the solution. The specified relative component mass ratios are retained by modifying the supplied volumetric distribution data. This is performed by calculating a constant volume fraction scaling factor for each component, then locally renormalizing the distribution so that the component volume fractions sum to unity. There is no special treatment of gas or dynamic powder at the burden surface.

The stock line zero level is the gas and dynamic powder outflow boundary. The top gas pressure and zero gradients for gas and dynamic powder velocity, enthalpy and composition and the dynamic powder volume fraction are specified here.

At the slag surface in the hearth, a solid temperature is specified and a conductive heat transfer boundary condition is used. Also, free liquid outflow is specified with zero gradients for all liquid properties.

At the top (throat) of furnace there were no static powders occurs. The solid flow field can be obtained directly from Eq. (4). However, the mass sources due to chemical reaction and energy conservation of static powder holdup have yet to be calculated in this study.

3. Results and Discussions

3.1. Validation of the Present Model

The model was applied to predict distributions of solid temperature in the blast furnace operation. The two-dimensional distributions of solid temperature for steady state condition were measured⁷⁾ in an operating blast furnace under three different PCI rates (100, 200 and 250 kg/thm) were carried out. The operating conditions used in this simulation are summarized in **Tables 1, 2 and 3** for the three-cases respectively. Three cases were presented for a furnace of inner volume 4550 m³. The figures are all drawn to the same scale. Temperatures were measured by thermocouples descending with the burden materials. When the probe temperature exceeded at 1200°C the temperature measurement was ceased. Therefore, for higher temperatures could not be compared in this paper.

Figure 2 shows the comparison between calculated and

Table 1. Operating condition for PCI: 100 kg/thm.

Blast temperature (°C)	1142
O ₂ (kg/s)	34.41
N ₂ (kg/s)	108.95
H ₂ O (kg/s)	0.1
Top gas pressure (atm)	2.64

Table 2. Operating condition for PCI: 200 kg/thm.

Blast temperature (°C)	1198
O ₂ (kg/s)	37.25
N ₂ (kg/s)	105.3
H ₂ O (kg/s)	0.1
Top gas pressure (atm)	2.64

Table 3. Operating condition for PCI: 250 kg/thm.

Blast temperature (°C)	1233
O ₂ (kg/s)	34.6
N ₂ (kg/s)	95.32
H ₂ O (kg/s)	0.1
Top gas pressure (atm)	2.64

Fig. 2. Comparison between calculated and measured temperature distributions for PCI: 100 kg/thm.

measured distributions of solid phase temperature for PCI rate 100 kg/thm. The calculated result shows a good agreement with the measured solid temperatures, especially for the high axial temperatures and lower shaft temperatures. The measured data shows a large zone of near-constant temperature between 900 and 1000°C, which is called the high temperature thermal reserve zone (HTRZ). Some furnaces also exhibit a second zone of near-constant temperature between 600 and 700°C, which is called the low temperature thermal reserve zone (LTRZ). The isotherm of 300°C calculated for this case located in higher position compared with the measured one. The first reason for this discrepancy is that the reaction rate was used in this model over predicted than the reaction rate proceeding in the blast furnace. The sizes of thermal reserve zone depend on local permeability in the packed bed caused by high holdup of powder and the relevancy of endothermic reaction. The second reason relates the reaction rate and interphase heat transfer. Either the model is over predicting the endothermic strength of the indirect reduction of magnetite to wustite or the interphase heat transfer rate is being underestimated due to the prediction a LTRZ which is larger than measured data. The most likely cause of the discrepancy from the second reason is under predicting reaction rate, as the model predicts the rate-limiting step of gaseous diffusion through the solid to the reaction interface. Detailed data about solid porosities was not available, thus porosity was estimated from literature correlation.⁸⁾ If the solid were more porous than assumed in the model, the calculated diffusion rate would be faster thus increasing the reaction rate and likewise the LTRZ size would decrease.

The second case analyzed was for PCI 200 kg/thm. The calculated solid temperature distribution compared with the measured one is shown in **Fig. 3**. For the region at the lower shaft of blast furnace, the model has been predicted the solid temperature accurately. Although, for the isotherm 300°C is still located in higher position than measured one. The discrepancy in isotherm 300°C is due to the same reason explained previously. In the middle shaft region of blast furnace, the calculated result was under predicted compared to the measured one. Actually, model under predicted the reaction rate of the solid gasification.

Figure 4 shows the comparison between measured and calculated distributions of solid temperature for PCI 250 kg/thm. A considerable agreement with the measured data has been achieved, especially for the upper shaft region. As the intensification of PCI decreases the coke consumption rate in blast furnace, it caused an increase of residence time of coke in the bosh part, thus increasing of the solution loss reaction time. Then the temperature at the root of cohesive zone (1200°C) was moved up due to the effect of the decrease heat flux ratio. Therefore, the temperature at the upper shaft increased with PCI, as shown in both calculated and measured result. Although for the calculated result shows that the HTRZ is located at the lower position.

Discrepancy of the calculated and measured results becomes significant as the PCI increases. The descending solid velocity of burden in upper part decreases, as the amount of coke consumption at the raceway decreases with increasing PCI. The solid phase is heated up with its descent by the heat exchange from gas flowing upward. In the

Fig. 3. Comparison between calculated and measured temperature distributions for PCI: 200 kg/thm.

Fig. 4. Comparison between calculated and measured temperature distributions for PCI: 250 kg/thm.

axial central part shows high temperature and form steep temperature gradient. Only the coke particles having larger diameter are fed to the centre of burden surface, and the permeability in the central part gets larger. This burden distribution enforces central gas flow, and the solid materials heated up quickly. With increasing PCI, the volume of gas phase passing through the packed bed increases, leading to the higher temperature in the upper part of the blast furnace, and this model successfully estimate this trend.

A series of calculations have been made to examine the effect of static powder holdup with increase in pulverized coal injection rates. The physical properties of powders

(fine particles) used in this simulation are listed in **Table 4**. Operational data for the furnace is given in **Table 5**. In the simulated cases oxygen enrichment was kept constant in order to maintain the combustion efficiency in the raceway similar to actual condition.⁹⁾

Figure 5 shows the distributions of static powder holdup in the blast furnace with increase in pulverized coal injection using calculation used by the Hidaka *et al.* The higher amount of static powder holdup volume fraction was found mostly in the central lower deadman, above and below the tuyere level, and also in upper shaft, especially for PCI rate 100, 150, 200 and 225 kg/thm, respectively. While the PCI rate increases, the combustibility of pulverized coal decreases; henceforth increases the unburned pulverized coal. The unburned pulverized coal out of the raceway will further react with slag, gas and hot metal somewhere in the furnace, resulting in a decrease in the gas and liquid permeability in the furnace. Static powder holdup makes a significant contribution to reduce the permeability in the deadman where the solid is almost stationary thus the amount of static powders holdup is large. At a low gas superficial velocity in deadman, unburned pulverized coal penetrates into the intermediate region of the deadman, and then accumulated

there. The increase accumulation of unburned pulverized coal in the bosh part, resulting the increase of residence time of coke, especially in the central lower deadman and below the tuyere nose. Therefore, much more fine powders stick to the surface of coke particle and/or space between coke particles and accumulate as become static-powder.

A significant change can not be observed for the static powder distribution in the lower part of blast furnace when PCI is over 150 kg/thm. This is due to in this model only the fine powders generated from unburned PC are considered. The other reason is a solid slip plane is simulated along the deadman surface by setting the viscous drag term in the solid momentum equations to zero between control cells which lie on either side of the deadman surface. Therefore in this model for PCI over 150 kg/thm the significant distribution of static powder can not be observed.

Above the tuyere nose, the solid flow into the raceway and the large vertical component of gas velocity caused unburned pulverized coal to move towards the furnace wall at that point. The net effect of unburned pulverized coal is to promote substantial static powders holdup in the region above tuyere towards the wall.

As shown from PCI rate 50 to 100 kg/thm, the cohesive zone at the belly region has tendency to move up. On the contrary, for PCI rate 100, 150, 200 and 225 kg/thm the cohesive zone is the same in all cases. This phenomenon is due to more gas cooling before reaching the axial cohesive zone. The increases in the amount of static powder holdup in the furnace, is caused by the greater gas solid heat transfer arising.

In this calculation, it was found higher value of static powders holdup in the upper shaft increases with PCI rate, which causes the decrease in descending velocity of solid particles. This phenomenon can be explained as follows. Since the amount of coke consumption (combustion) at the raceway decrease with an increase in PCI rate, it promotes the void in the packed bed particles to decrease, and conse-

Table 4. Physical properties of powder (fine particle) to analyse static powder holdup in blast furnace.

Diameter (m)	1.0×10^{-4}
Density (kg/m^3)	500

Table 5. Operational parameter to analyse static powder holdup in blast furnace.

PCR (kg/thm)	57	100	150	200	225
Coke rate (kg/thm)	440	410	365	320	310
O ₂ enrichment (%)	3	3	3	3	3
Combustion efficiency (%) [given value]	90	83	78	73	68
Unburned char rate (kg/thm)	10.3	24.4	43.4	67.0	85.6

Fig. 5. Static powder holdup distributions with increased pulverized coal injection (PCI) in the blast furnace.

quently the descending velocity of solid particles also decreases more and more.

The lower amount of static powder holdup was found in front of the tuyere nose and along the surface of deadman. This is due to the small resistance of gas permeability in these regions as compared to the other regions.

These calculations can predict the distribution of static powder holdup in blast furnace operation. However, at present there is no concluded data available that gives an accurate quantitative amount of static powders in blast furnace.

4. Conclusion

A numerical analysis of static powder holdup in the blast furnace has been performed. The developed model adopted the “four fluid model”, which included the formulation of static powder behavior. This model can be used to predict a quantitative analysis static powder holdup in the blast furnace operation. The higher amount of static powder holdup volume fraction was found mostly in the central lower deadman, above and below the tuyere level, and also in upper shaft, especially for PCI rate 100, 150, 200 and 225 kg/thm, respectively. The lower amount of static powders holdup was found in front of the tuyere nose and along the surface of deadman.

Nomenclature

d_f :	Diameter of powder	[m]
G_f :	Feed rate of dynamic powders	[kg/m ² s]
G_g :	Feed rate of gas	[kg/m ² s]
$k_f a$:	Apparent coefficient of accumulating rate of powders to the surface of solid	[s ⁻¹]
$k_r a$:	Apparent coefficient of returning rate of powders to the gas stream	[s ⁻¹]
r :	Radial spatial coordinate	[m]
r_s :	Adhering rate of powders	[m ³ /s]
r_d :	Departing rate of powders	[m ³ /s]
R_f :	Depositing rate of powders	[m ³ /s]

S_ψ :	Source term for variable	[various]
u_i :	Interstitial axial velocity component of phase i	[m/s]
u_f :	Linear velocity of powders	[m/s]
u_g :	Linear velocity of gas	[m/s]
u_z :	Hypothetical critical gas velocity to produce discharge of fine	[m/s]
v_i :	Interstitial axial velocity component of phase i	[m/s]
x :	Axial spatial coordinate	[m]

Greek letters

ε_i :	Volume fractions of phase i (i : gas, solid, metal, slag, dynamic-powders, static powders)	[m ³ /m ³ bed]
ε_{fo} :	Dynamic powders holdup defined as volume fraction of fines in packed bed	[—]
ε_{iso} :	Static powders holdup defined as volume fraction of fines in packed bed	[—]
ρ_i :	Density of phase i	[kg/m ³]
Γ_ψ :	Exchange coefficient for variable ψ	[various]
ζ :	Diffusive variable in Eq. (1)	[various]
ψ :	General dependent variable in Eq. (1)	[various]

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