Numerical Analysis on Behavior of Unburned Char and Fine Coke in Blast Furnace

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A mathematical model of blast furnace operation, which is able to estimate the behaviors of the unburned char and the fine coke simultaneously, has been developed. The model based on the multi-fluid theory treats dynamic powders that are moving entrained by the gas stream as individual phases and static powders as solid components. The former takes conservation equations of momentum, thermal energy, chemical species and continuity. The latter takes only mass balance equations of chemical species, and shares fields of flow and temperature with the other solid components, such as lump coke, sinter, and so on. In the simulations, the unburned char is derived from the pulverized coal injected from the tuyere, and there is no difference in model treatment between the unburned char and the pulverized coal. The fine coke is generated uniformly in the raceway region from the coke particles, and the generation rate is determined by a kinetic treatment. The simulation of the blast furnace operation by this model revealed that the unburned char and the fine coke having different diameters and densities show different flow patterns especially in the cohesive zone and deadman. Consequently these two powders formed different areas of accumulation and reactions while large amount of powders were deposited in the deadman zone regardless of difference in flow patterns.

KEY WORDS: blast furnace; powder accumulation; flow characteristics; unburned char; fine coke; numerical analysis; reactions.

1. Introduction

Powder behavior in the lower part of blast furnace has been attracting technical and scientific interests with recent increase in pulverized coal injection rate into blast furnace through tuyere.1–5) Under high pulverized coal injection rate condition, not only unburned char but also fine coke particles increases in lower zone of blast furnace.6,7) Accumulation of such fine particles in the furnace deteriorates permeability of the packed bed,8) which may cause instability of furnace operation. Therefore powder behavior in the lower part of blast furnace needs to be quantitatively understood to keep stable furnace operation. Powder deposition in actual blast furnace is complex phenomenon that consists of several generation mechanisms, reactions, multiphase flow, accumulation and reentrainment. Thus a lot of approaches such as mechanics on coke degradation, reaction kinetics on pulverized coal combustion, fluid dynamics on powder motion, etc. have been carried out to clarify powder deposition behavior. Among these approaches, numerical simulation of powder motion based on multiphase fluid dynamics is expected to be a useful tool to estimate packing structure in the lower part of the blast furnace. Fundamental flow mechanics such as traveling velocity of powders and interaction forces among gas, fine powders and packed particles were measured, and mathematical models based on these works were proposed.9–16) Although these models successfully simulated powder motion and pressure drop within packed beds, all models except for Yamataoka’s work16) treat powders as dynamic hold-up or moving total hold-up, and are incapable of taking into account static hold-up and accumulation behavior. The authors have developed mathematical models of blast furnace, which are based on multi-fluid theory.17–21) Recently these models included accumulated powder (static hold-up) as a new phase to analyze powder deposition behavior of powder in blast furnace and granular bed filter.22–24) Although these models provided the useful information and expectations, simultaneous handling of the pulverized coal and the fine coke with dynamic-static separation has yet to be reported. In this study a multi-fluid based operation simulator of blast furnace including this feature and heat transfer and chemical reactions regarding accumulated powders was developed, and this new mathematical model was applied to the actual blast furnace operation to examine the behaviors of the unburned char and the fine coke in the blast furnace.

2. Mathematical Models

In this study the mathematical model of the blast furnace operation developed by the authors22,24) is extended to treat
the unburned pulverized coal and the fine coke as individual materials and to take into account static hold-ups of these two powders. The previous model \cite{25} was already able to handle two kinds of dynamic powders and applied to the operation analysis on simultaneous injection of pulverized coal and flux material or pre-reduced iron. Although this model considered only dynamic powders, this two-powder treatment was taken over by the newly developed model. Two powders considered in this study are pulverized coal (or unburned char) and fine coke. Although these two powders have similar chemical compositions, they show different physical properties, particle structure, and so on. The fine coke is generated as the coke fragments detached from the lump coke particles. Thus it fundamentally has same chemical components and properties as the lump coke particles but the diameter. Contrarily the pulverized coal undergoes chemical and thermal processes during its combustion process. As a result, the unburned char usually has a porous structure and shows various textures such as network, balloon, skeleton, and so on. It is usually considered that the unburned char has smaller average diameter and apparent density than the fine coke. Consequently these two powders indicate different fields of flow, temperature and reaction each other. Therefore the unburned char and the fine coke are treated as different phases in this model. The behaviors of these two phases are described by the conservation equations of momentum, heat and chemical species and continuity equations. These equations are expressed by a single generalized form.

\[
div(\varepsilon \rho \vec{u} \phi) = \text{div}(\Gamma_\phi \text{grad} \phi) + S_\phi + \sum_j F_{\phi,j} = 0 \quad \text{(1)}
\]

Replacing the symbol \(\phi\) with the variable to be solved, the conservation equation can be obtained, for example, velocity for momentum conservation, enthalpy for heat balance, mass fraction of chemical species for material balance and unity for continuity. The subscript “i” means phase, and pulverized coal and fine coke take different suffices since these are different phases as mentioned above. The source term \(S_\phi\) evaluates reaction, reaction heat, gravity, and so on. The last term \(F\) takes into account the exchanges of mass, momentum, heat and material with the other phases. Two powders take same mechanisms of momentum and heat exchanges. These rates are estimated by the previously reported methods.\cite{17,18,25} The chemical reactions for the pulverized coal phase are devolatilization, carbon combustions, water gas and solution loss reactions.\cite{18} The fine coke phase undergoes the same reactions as coke in solid phase, solution loss, water gas, carbon combustions and melting of ash. For the fine coke reaction the reaction parameters as solid lump coke\cite{18} but reaction surface area and gaseous mass transfer parameter are applied. These two parameters are estimated by the same method as the pulverized coal phase, namely ones of a single spherical particle in the gas flow.

Regarding the static powders, their treatment was changed from the previous work.\cite{22,24} The static powder is treated as a component of the solid phase in the modified model while the previous model handles it as a phase. The solid phase consists of multiple components, such as coke, lump ore, sinter, pellet, and so on. These components have only material balance equations and share temperature and velocity fields among the solid components. The phases have momentum and heat balance equations and continuity equations. This modification schematically shown in Fig. 1 was made because the static powder sticks to the surface or interstice of charged materials and moves along with these materials. Additionally the heat exchange rate between the static powder and solid particle in the packed bed has yet to be formulated. Note that phases of liquid and dynamic powder and static powder are further separated into two phases or materials each in the actual simulation although these phases and materials are put together in this figure.

In the previous treatment, the continuity equation of the static powder phase gives the volume fraction of static powder. Contrarily the material balance equations regarding the static powder as a component of solid phase give the mass fraction of chemical species belonging the static powder. Therefore the volume fraction of the static powder is calculated by the following manner from the mass fraction. In the blast furnace, the solid components are usually charged to form layered packed structure as shown in Fig. 2(a). The mathematical model assumes that the packed ratio (or voidage) of single component bed is known. With this assumption and volume ratio of each single component bed (\(\varepsilon_i^b\) and \(f_i\) in Fig. 2(a)), the averaged voidage of the burden materials can be calculated. The volume ratio of component “i” can be calculated based on the mass fraction \(\omega_i^b\) and density \(\rho_i^b\) of each bed.

\[
f_i = \frac{(\omega_i^b / \rho_i^b)}{\sum_k \omega_k^b (\omega_k^b / \rho_k^b)} \quad \text{(2)}
\]

Therefore the volume fraction of solid phase without static powder phase can be given by the following equation.

\[
\varepsilon_{\text{b, burden}} = \sum_j \frac{\varepsilon_j^b (\omega_j^b / \rho_j^b)}{\sum_k \omega_k^b (\omega_k^b / \rho_k^b)} \quad \text{(3)}
\]

The deposited (static) powder is postulated to exist in the interstice of packed particles as shown in Fig. 2(b). In this treatment, volume fraction of static powder in deposited layer is assumed to be known. The volume fraction of static powder is given based on the mass ratio of the static powder to the burden materials.
Finally volume fraction of solid phase can be obtained as

$$E_s = E_{\text{burden}} + E_{\text{sd}}$$ ...........................(5)

Powder deposition is treated as mass exchange between dynamic powder phase and static powder component. This rate is expressed as the difference between sticking and reentrainment rates based on the method proposed by Hidaka et al.\textsuperscript{22,26)

$$F_{1d-\text{sd}} = r_s - r_d$$ .................................(6)

The inter-phase transfer rates of chemical species accompanying the powder deposition are given by the following equation.

$$F_{(w_k)1d-\text{sd}} = r_k \cdot \omega_{k\text{-sd}} - r_d \cdot \omega_{k\text{-fs}}$$ ..............................(7)

The mass fractions of “k”th chemical species in dynamic powder phases and static powder components are normally different each other because they experience different reaction histories.

The generation of fine coke is treated as the inter-phase mass transfer from lump coke (component of solid phase) to the dynamic fine coke phase. The fine coke generation rate is calculated by the method proposed by Watakabe et al.\textsuperscript{27) This method tracks the reaction of a coke particle to determine degradation rate. The raceway is assumed to consist of jet region with high oxygen concentration and transition region with high carbon dioxide concentration. The coke particle alternately undergoes carbon combustion at the particle surface and solution loss reaction within the particle while the particle passes through two regions during recirculation in the raceway. The latter reaction forms the degradation layer in the particle and the former reaction consumes this layer. The fine coke particle is generated from the degradation layer, and this rate is calculated based on the voidage of the degradation layer and the stress acting on the particles. The reaction condition and the particle kinetic energy in the raceway zone are determined based on the simulation results of the blast furnace simulator. Then the fine coke generation rate calculated by this method is input to the blast furnace simulator. This procedure is iterate until the fine coke generation rate becomes constant. Note that the fine coke is generated uniformly over the raceway zone in the blast furnace simulator.

3. Results and Discussion

The mathematical model that included behavior of two powders was applied to the simulation of the blast furnace operations. The major conditions used in the simulation are listed in Table 1 and Fig. 3. The furnace has inner volume of 4397 m\(^3\) and produces 10462 t/d of hot metal. The coke rate and pulverized coal injection rate are 369 and 126 kg/thm, respectively, and the reducing agent rate is 495 kg/thm. The blast volume, temperature and oxygen enrichment are 7283 Nm\(^3\)/min, 1138°C and 2.5%. The burden distribution showing the higher ratio of iron bearing materials in the mid-radial part was applied. For all computations, diameters and densities were set at 0.1 mm and 500 kg/m\(^3\) for the unburned char and 1.0 mm and 1000 kg/m\(^3\) for the fine coke, respectively. The properties of unburned char is determined under the assumptions of the swelling factor of 1.1

Table 1. Major conditions for simulation of blast furnace operation.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner volume</td>
<td>4359 m(^3)</td>
</tr>
<tr>
<td>Productivity</td>
<td>10460 tld</td>
</tr>
<tr>
<td>RAR</td>
<td>495 kg/thm</td>
</tr>
<tr>
<td>PCR</td>
<td>126 kg/thm</td>
</tr>
<tr>
<td>Blast volume</td>
<td>7283 Nm(^3)/min</td>
</tr>
<tr>
<td>Blast temp.</td>
<td>1138 °C</td>
</tr>
<tr>
<td>O(_2) enrichment</td>
<td>2.5%</td>
</tr>
</tbody>
</table>

Fig. 3. Burden distribution used in the simulation.
and burned ratio in the raceway of 55%. Regarding the fine coke, the particles having the diameter smaller than 3 mm are usually treated as fine coke. Thus the 1 mm is adopted as the characteristic diameter of fine coke.

Figure 4 shows the temperature distributions of solid phase for the cases handling (a) only dynamic unburned char, (b) unburned char and fine coke but no accumulation and (c) dynamic and static powders of both unburned char and fine coke. All distributions were shown in a half cross section including the center axis of the furnace because the computations were performed in the framework of axisymmetry. The location and shapes of the cohesive zone and the deadman are depicted by the dotted lines. All cases showed that the temperature distribution high in the central and near wall regions and low in the mid-radial part due to the burden distribution shown in Fig. 3. Consequently the “W”-shaped cohesive zone is formed in all cases. Comparing dynamic powder cases, overall distributions are similar to each other while the location of the cohesive zone is slightly higher in the two-powder case. The case with two powders and accumulation shows formation of the low temperature zone in the deadman while the distribution in the upper part is similar to the other cases.

The gas flow patterns calculated under the conditions with and without static powder accumulation are shown in Fig. 5. In both case, gas introduced from the tuyere flows out from the raceway zone to various directions. The gas flow ascending the furnace changes its direction around the cohesive zone due to the anisotropic permeability of this zone. In the shaft part the gas stream shows two main flow region, namely central part and near-wall regions because of the radial distribution of charged materials. The difference between these two cases are significant in the deadman zone. The gas velocity becomes smaller when the powder accumulation is considered. This difference in the gas flow behavior results in the increase in the pressure drop in the case with powder accumulation. The pressure differences between the burden surface and the computation cell in front of the tuyere were 67.5 kPa for no static powder case and 79.8 kPa for static powder case. This increase in the pressure drop was caused mainly by the strengthened upward gas flow above the raceway zone due to the narrowed gas flow path by the powder accumulation.

The flow patterns of dynamic unburned char and fine coke are shown in Fig. 6. The flow pattern of the unburned pulverized coal follows one of the gas phase while its value is generally smaller than gas phase except for tuyere nose. The flow pattern of fine coke is similar to the gas flow pattern in general. The velocity of the fine coke is further smaller because of the larger friction force with the packed particles due to its larger diameter. The difference in the flow pattern appears in the deadman and the cohesive zone. In these regions the direction of the gas stream becomes almost horizontal. This flow pattern diminishes upward interaction force acting on the fine coke. Furthermore the down-
ward gravitational force acts stronger to the fine coke particles having higher density. Consequently the downward flow of the fine coke appears in the deadman and the cohesive zone.

Figures 7 and 8 show the distributions of volume fractions of the unburned char and the fine coke. The unburned char introduced from the tuyere mainly flows upward after leaving the raceway zone. The dispersion in the horizontal direction is small and the higher fraction zone is formed in the mid-radial region throughout the furnace height. This tendency is same when the powder accumulation is taken into account while the value of the volume fraction becomes smaller. The fine coke shows the high volume fraction zone in the central bottom region due to its flow pattern shown in Fig. 6. The fine coke ascends slowly from this high concentration zone, and this high fraction zone stretches upward near the center axis. This tendency of volume fraction of fine coke was same in the case with powder accumulation.

Regarding static powders, the static hold-up of both powders show higher value in the deadman zone. This accumulated powders deteriorate the permeability of deadman zone and weaken the gas flow in this region as shown in Fig. 5. Consequently the heat supply to the deadman zone by the hot gas flow decreases and the low temperature zone is formed in the deadman zone as shown in Fig. 4(c). This mechanism of the deadman cooling was expected in the previous work without taking into account the powder accumulation. The unburned char and the fine coke show different accumulation zones in the region higher than the deadman zone. The unburned char shows higher static hold-up above the raceway zone, and the fine coke does in the region closer to the center axis. These difference is brought by the difference in the main flow region of dynamic powders as shown in Fig. 7.

Fig. 7. Volume fractions of dynamic unburned char and fine coke.

Figure 9 shows the distributions of powder deposition rates of the unburned char and the fine coke. In the center bottom of the deadman region the deposition rate shows negative value, in other ward the reentrainment of the static powder takes place irrespective of weak gas flow in this region. This is considered due to the higher amount of accumulated powder. The re-entrainment of static powder occurs also beneath the cohesive zone and in the upper shaft. In these regions strong gas flow blows off the accumulated powders. The strong powder deposition zone is formed above the root of the cohesive zone. The gas flow

Fig. 8. Volume fractions of static unburned char and fine coke.

(a) unburned char (b) fine coke

0.5 % 1.0 % 5.0 %
10.0 % 15.0 %

(a) no static (b) with static

Unburned char Fine coke

0.0005 % 0.0010 %
0.0015 % 0.0020 %
0.0025 %
2 % 6 % 8 %
10 %
turns its direction around the cohesive zone and the weak gas flow region is formed in this area, and this makes powders to deposit easily in this region.

Figure 10 shows the distributions of the solution loss reaction rates of coke, accumulated unburned char and fine coke. The main zones of the solution loss reaction are around the raceway and in and above the cohesive zone. The static fine coke shows fast reaction zone only in the cohesive zone due to its small amount of accumulation around the raceway zone. Around the cohesive zone, the static fine coke undergoes the solution loss reaction in whole thickness of cohesive zone while the coke reaction area locates down to the middle of cohesive zone. The volume fraction of static fine coke is very small above the cohesive zone and the reaction surface area of the fine coke is larger than coke in the cohesive zone due to the particle diameter. These factors make the difference in the reaction behavior of the lump coke and the fine coke. The reaction zone of the solution loss of unburned char starts just beneath the cohesive zone and show wider range of height than the other materials. The value of the reaction rate, however, is smaller than the lump coke and the fine coke due to the small accumulation of the static unburned char. With such reactions the chemical compositions of both dynamic and static powders vary with location. Consequently the exchange rates of chemical species between dynamic and static powders are not in proportion to the powder deposition rate. Figure 11 compares the rates of unburned char deposition and accompanying carbon exchange. In the figure only the contour of 0 g/m³/s is drawn. Although the tendency of the distributions are similar to each other, some portions especially in the lower part show the differences. This difference is formed by the difference in the chemical compositions of static and dynamic powders.

4. Conclusions

A mathematical model of blast furnace operation, which is able to estimate the behaviors of the unburned char and the fine coke at the same time, has been developed in this study. The model handles the dynamic hold-ups of these two powders as individual phases and the static hold-ups as the components of solid phase. The simulation of the blast furnace operation by this model revealed that the unburned char and the fine coke having different diameters and densities showed different flow patterns, areas of accumulation and reaction zones.
Nomenclature

\( f_i \): Volume ratio of component “i”

\( F_{\phi_{i-m}} \): Inter-phase exchange rate of variable “\( \phi_i \)”

\( r_d \): Re-entrainment rate of powder (kg/m\(^3\)s)

\( r_s \): Sticking rate of powder (kg/m\(^3\)s)

\( S_{\phi_i} \): Source term for variable “\( \phi_i \)”

\( \bar{u} \): Velocity (m/s)

\( e_{i0} \): Volume fraction of component “i” in single component bed

\( G_{fi} \): Effective diffusivity (m\(^2\)/s)

\( w_{ib} \): Mass fraction of component

\( \rho_i \): Density (kg/m\(^3\))

\( \rho_{i0} \): Density of single component bed (kg/m\(^3\))

Subscript

sf: Static fine

s: Solid

burden: Burden materials

REFERENCES

6) K. Takeda and N. Ishiwata: CAMP-ISIJ, 10 (1997), 123.