1. Introduction

The blast furnace process is a counter current moving bed chemical reactor whose main purpose is to reduce iron oxides to iron. In the actual blast furnace operation the iron oxides are charged as iron ore/sinter/pellets to the top of the blast furnace. The iron bearing materials start to melt and form a cohesive zone. Formation of cohesive zone is regarded as one of the most restrictive factor for increasing the blast furnace productivity due to its high flow resistance. Another critical parameter is the slag accumulation just beneath the cohesive zone. Slag can be hung up in this region by the gas stream and promotes irregular gas flow, which in turn, will lead to unstable furnace operation. Aiming to avoid these problems and increase the blast furnace productivity, multiple injection of pre-reduced fine ore, flux and pulverized coal to the blast furnace tuyere has been proposed. If only iron ore is injected, reduction of iron oxides and melt of gangue materials in and around the raceway zone tends to decrease the temperature in this region. The temperature decrease promotes increase in slag viscosity then poor slag flow. The slag viscosity also closely relates to the slag composition, therefore combined injection of pre-reduced fine ore and flux is expected to overcome the slag fluidity problem by modifying slag composition. In addition sufficient energy should be supplied to this region to avoid accumulation of partially melted materials around the raceway and formation of raceway shell, which promotes irregular gas distribution and inactiveness of dead man. Simultaneous injection of pulverized coal can supply sufficient energy to this region. Moreover extra flux materials injected through the tuyere can decrease flux charge to the top and consequent decrease in the slag formation in the cohesive zone. Several studies have been carried out in order to elucidate the multiple injection phenomena and fundamental experiments have been proposed in order to simulate the blast furnace operating with multiple injection. However, a detailed mathematical model, which is capable of simulating the multiple injection through the blast furnace tuyere, has not yet been reported. In this paper a mathematical model of the blast furnace is presented to simulate the blast furnace operation with multiple injection of pulverized coal, pre-reduced fine ore and flux. The model is based on the multi-fluid theory and considers explicitly six phases (gas, lump solids, pig iron, molten slag, pulverized coal and pre-reduced iron ore/flux). Each phase has own composition and properties, and reactions of all phases can be considered to simulate process of multiple injection. Moreover, the silicon content can be lowered and the furnace productivity can be largely increased.

KEY WORDS: blast furnace; mathematical model; multi-phase flow; pulverized coal injection; iron ore injection; flux injection.
and the effects of this method were examined.

2. Mathematical Model

2.1. General Conservation Equation

The mathematical model is two dimensional and axisymmetric. It analyses the packed bed region within the blast furnace, from the surface of the slag in the hearth up to the burden surface in the throat. Unlike previous model\(^\text{12,13)\)} this model handles pulverized coal and pre-reduced fine ore/flux as different phases. Therefore, in order to simulate multiple injection the model considers six phases in the packed bed, namely, gas, solids, hot metal, molten slag, pulverized coal and pre-reduced fine ore/flux. Each phase consists of one or more components having its own composition and physical properties. All phases are treated at the same time because those phases interact with one another. Thus the governing equations of all materials, that form a large set of strongly coupled equations, are solved simultaneously. In this model conservation equations for the pre-reduced fine ore/flux are newly introduced to describe the fields of velocity, volume fraction, chemical species and energy for this new phase.

Governing conservation equations for all phases are expressed via a general equation, represented by Eq (1), which is independent of the coordinate system.

\[
\frac{\partial (\varepsilon_i \rho_i \psi_i)}{\partial t} + \text{div} (\varepsilon_i \rho_i \vec{V}_i - \varepsilon_i \vec{F}_i \text{grad} \psi_i) = S_{\psi_i} \quad \ldots \ldots \text{(1)}
\]

In this equation \(i\) represents the phase being considered. The complete set of chemical species for each phase considered in this model is summarized in Table 1. The other variables considered are the phase velocity components, pressure or volume fraction and energy. The source terms are due to inter-phase interactions that can be through chemical reactions and surface interactions or external force.

2.2. Source Terms

The source terms in the conservation equations take into account chemical reactions, interactions, external force, phase changes and so on. The continuity and species equations have mass sources due to chemical reactions and phase transformations. Enthalpy sources arise from inter-phase heat transfer, heat of reaction and sensible heat transfer accompanying mass transfer due to chemical reactions and phase transformations. The formulations for the phase interactions and chemical reaction have been published in previous reports.\(^\text{12,13)\)} In this section, details of interactions concerned with pre-reduced fine ore/flux, added as new phase, are explained. The interaction between gas and pre-reduced fine ore/flux is modeled based on the drag force of a single particle moving in a fluid, which is modified to take into account the existence of neighboring particles.\(^\text{14,15)\)} The interaction between solid and pre-reduced fine ore/flux is modeled based on Fanning’s equation.\(^\text{16)\)} No interaction between fine particles and liquids is considered. Heat transfer between pre-reduced fine ore/flux and gas is calculated by Ranz-Marshall equation\(^\text{17,18)\)} and pre-reduced fine ore/flux solid heat transfer coefficient is derived from an emulsion model of gas-fine system.\(^\text{19)\)} Detailed formulation of the source terms for momentum and heat transfer of the pre-reduced fine ore/flux is presented in Table 2.

2.3. Behavior of Pre-reduced Fine Ore/Flux Phase

The pre-reduced fine ore injected into the combustion zone of the blast furnace is heated up and reduced in contact with carbon monoxide and melts. On the other hand, flux and gangue materials melt and generate slag. Eventually some particles cannot be completely melted in
this region due to short residence time. Even in this case, reactions and phase transformation proceeds while the particles flow through the packed bed. This model uses the three-interface model to simulate the fine iron ore reduction as schematically shown in Fig. 1. Phase transformations of iron bearing materials is assumed to occur when iron oxides reach wustite stage. Melting of wustite, iron ore and gangue materials are allowed to occur when the temperature of fine ore/flux phase reaches melting point of these materials. Molten wustite transferred to the slag phase is finally reduced to iron by direct reduction. Table 3 summarizes all the chemical reactions and phase transformations concerned with pre-reduced fine ore/flux phase. The rate equation for chemical reaction can be found in the literature.\(^\text{12,13}\)

3. Results and Discussions

3.1. Calculating Conditions

Two series of calculations were performed. One is pre-reduced fine ore injection (practice 1) and the other is injection of pre-reduced fine ore and flux (practice 2). In all cases analyzed the pulverized coal injection rate was kept constant. To examine the effect of pre-reduced fine ore and flux injection, the hot metal temperature was selected as key control value. Enrichment of oxygen to the blast gas was adjusted to maintain hot metal temperature (average temperature of molten metal phase passing through the bottom of the calculation domain). The amount of oxygen added to the blast was determined by “trial and error” method. Concretely, flow rates of pulverized coal, pre-reduced fine ore and flux are fixed and blast conditions are specified first. Then simulating calculation is performed and then estimated hot metal temperature is compared with a reference value. If the difference between calculated and reference temperature is larger than 10 K, oxygen enrichment in the blast is adjusted and computation is carried out again. The adjustment of tuyere conditions and solution of the equations are iterated until the temperature difference becomes less than 10 K. The reference temperature was taken from the base case in which no pre-reduced fine ore

![Fig. 1. Schematic diagram of chemical reactions and phase transformation for fine ore and flux.](image)

| Table 3. Chemical reactions and phase transformations concerned with pre-reduced fine ore/flux phase. |
| --- | --- |
| **Indirect reduction by CO** | **Melting of fine phase** |
| \(3\text{Fe}_2\text{O}_3\text{(FO)} + \text{CO(g)} \rightarrow 2\text{Fe}_2\text{O}_4\text{(FO)} + \text{CO}_2\text{(g)}\) | \(\text{Fe}_3\text{O}_4\text{(FO)} \rightarrow \text{Fe}_3\text{O}_4\text{(slag)}\) |
| \(\frac{n}{4n - 3}\text{Fe}_2\text{O}_3\text{(FO)} + \text{CO(g)} \rightarrow \frac{3}{4n - 3}\text{Fe}_2\text{O}_4\text{(FO)} + \text{CO}_2\text{(g)}\) | \(\text{Fe}(\text{FO}) \rightarrow \text{Fe(metal)}\) |
| \(\text{Fe}_3\text{O}_4\text{(FO)} + \text{CO(g)} \rightarrow w\text{Fe}(\text{FO}) + \text{CO}_2\text{(g)}\) | \(\text{CaO}(\text{FO}) \rightarrow \text{CaO(slag)}\) |
| \(\text{Indirect reduction by H}_2\) | \(\text{MgO}(\text{FO}) \rightarrow \text{MgO(slag)}\) |
| \(3\text{Fe}_2\text{O}_3\text{(FO)} + \text{H}_2\text{(g)} \rightarrow 2\text{Fe}_2\text{O}_4\text{(FO)} + \text{H}_2\text{O(g)}\) | \(\text{Al}_2\text{O}_3\text{(FO)} \rightarrow \text{Al}_2\text{O}_3\text{(slag)}\) |
| \(\frac{n}{4n - 3}\text{Fe}_2\text{O}_3\text{(FO)} + \text{H}_2\text{(g)} \rightarrow \frac{3}{4n - 3}\text{Fe}_2\text{O}_4\text{(FO)} + \text{H}_2\text{O(g)}\) | \(\text{SiO}_2\text{(FO)} \rightarrow \text{SiO}_2\text{(slag)}\) |
| \(\text{Fe}_3\text{O}_4\text{(FO)} + \text{H}_2\text{(g)} \rightarrow w\text{Fe}(\text{FO}) + \text{H}_2\text{O(g)}\) | \(\text{gangue}(\text{FO}) \rightarrow \text{gangue (slag)}\) |
| **Direct reduction by Carbon** | **Melting of fine phase** |
| \(\text{Fe}_3\text{O}_4\text{(slag)} + C(\text{coke}) \rightarrow w\text{Fe (metal)} + \text{CO(g)}\) |
and flux is injected. In other words, only pulverized coal is introduced into the tuyere as injectant in the base case. Major operating conditions and burden distribution for the base case are summarized in Table 4 and Fig. 2. This burden distribution is also used for all cases.

In the operational practice 1, pre-reduced fine ore is injected at the rates of 15, 30, and 80 kg/thm. For the practice 2, total injection rates of pre-reduced fine ore and flux were 60, 120 and 250 kg/thm, and the ratio of pre-reduced fine ore to flux was constant (ore : flux = 70 : 30% mass). In addition, for the practice 2, half amount of injected flux components was deducted from the charged materials. The chemical composition of pre-reduced fine ore and flux are summarized in Table 5. The iron ore used in this study is classified as highly pre-reduced and this choice was motivated by its benefits to the blast furnace. When pre-reduced iron ore is used, it is possible to increase the blast furnace performance and reduce the coke rate, since no additional energy is required to reduce the fines injected through the blast furnace tuyeres. Moreover, if only fine hematite is injected, the injection rates are limited by highly endothermic reactions, since considerable amount of melted iron oxides must be reduced in the lower part of the blast furnace. In order to check the wholesome of the simulations carried out in this study, the elemental mass balance of the major elements are selected. This model uses as one of the convergence criteria the mass balance of the species considered in the mathematical model. Usually when the error of mass balance is lower than 1% the model checks the other variables to decide if the calculation can be finished. Therefore, is expected that the errors in elemental balance also locate in this range, which is promptly verified in Table 6.

### 3.2. Sensibility of the Operational Parameters to Multiple Injections

Figure 3 shows the effects of pre-reduced fine ore/flux injection on the blast furnace operation. The hot metal production increases with the injection rate of pre-reduced fine ore and flux. Enriched oxygen is about 7% and 17% at the maximum injection rate of both practices. Extra oxygen was blown in order to maintain hot metal temperature and resulting in increase in carbon consumption in the combustion zone of the blast furnace. The solid composition and charging pattern is fixed and the solid inflow is defined by the total amount of carbon of coke consumed. The reaction rates involving carbon of coke are strongly dependent of temperature pattern within the blast furnace. On the other hand, the presence of high concentration of oxygen in the raceway drives the combustion reactions. The solid inflow is corrected dynamically until the equilibrium of phase energy and chemical reaction rates is achieved. The solid descending velocity, established by the carbon consumption, promotes inflow of iron bearing materials, since the different solids components is assumed in a unique phase possessing same velocity field. The iron bearing materials are then reduced in the upper part of the blast furnace and the remaining iron oxide is melted as wustite. The wustite direct reduction is a step relatively fast and requires considerable amount of energy.

### Table 4. Major operational parameters for the base case.

<table>
<thead>
<tr>
<th>Blast conditions</th>
<th>Calculated parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>1198 (°C)</td>
</tr>
<tr>
<td>Production rate</td>
<td>103.5 (kg/s)</td>
</tr>
<tr>
<td>Flow rate</td>
<td>144.1 (kg/s)</td>
</tr>
<tr>
<td>Slag rate</td>
<td>261 (kg/thm)</td>
</tr>
<tr>
<td>O2 enrichment</td>
<td>0.7 (%)</td>
</tr>
<tr>
<td>PC</td>
<td>200 (kg/thm)</td>
</tr>
<tr>
<td>Humidity</td>
<td>15 (g/Nm³)</td>
</tr>
<tr>
<td>Coke rate</td>
<td>309 (kg/thm)</td>
</tr>
</tbody>
</table>

### Table 5. Chemical composition of pre-reduced fine ore and flux

<table>
<thead>
<tr>
<th>Fine ore mass (%)</th>
<th>Fe₂O₃</th>
<th>FeO₂</th>
<th>FeO</th>
<th>Fe</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>MgO</th>
</tr>
</thead>
<tbody>
<tr>
<td>24.4</td>
<td>3.2</td>
<td>29</td>
<td>40</td>
<td>2.1</td>
<td>1.2</td>
<td>0.1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fine flux mass (%)</th>
<th>CaO</th>
<th>MgO</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>30</td>
<td></td>
</tr>
</tbody>
</table>

### Table 6. Elemental balance for major components.

<table>
<thead>
<tr>
<th>Element</th>
<th>Base</th>
<th>Fine ore</th>
<th>Fine ore +Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>93.97</td>
<td>97.5</td>
<td>201.3</td>
</tr>
<tr>
<td>Output</td>
<td>93.52</td>
<td>96.67</td>
<td>208.1</td>
</tr>
<tr>
<td>Error (%)</td>
<td>-0.48</td>
<td>-0.85</td>
<td>-1.01</td>
</tr>
<tr>
<td>Input</td>
<td>99.87</td>
<td>101.8</td>
<td>185.0</td>
</tr>
<tr>
<td>Output</td>
<td>100.6</td>
<td>102.7</td>
<td>185.2</td>
</tr>
<tr>
<td>Error (%)</td>
<td>+0.70</td>
<td>+0.87</td>
<td>+0.48</td>
</tr>
<tr>
<td>Input</td>
<td>44.72</td>
<td>44.9</td>
<td>89.7</td>
</tr>
<tr>
<td>Output</td>
<td>44.26</td>
<td>45.3</td>
<td>90.5</td>
</tr>
<tr>
<td>Error (%)</td>
<td>-1.03</td>
<td>+0.88</td>
<td>+0.89</td>
</tr>
<tr>
<td>Input</td>
<td>1.88</td>
<td>1.97</td>
<td>3.67</td>
</tr>
<tr>
<td>Output</td>
<td>1.90</td>
<td>2.00</td>
<td>3.69</td>
</tr>
<tr>
<td>Error (%)</td>
<td>+1.05</td>
<td>+1.50</td>
<td>+0.54</td>
</tr>
</tbody>
</table>

Fig. 2. Burden distribution pattern used as boundary condition at the top for solid phase.
which will reflects again in the chemical reactions and energy conservation. Therefore, the increase in productivity is the result of this equilibrium. Ultimately, when additional oxygen is introduced, the combustion with coke will furnishes the necessary energy and the limit of this process is dictated by the burden pattern (Lo/Lc) and the established in-furnace condition. The amount of additional oxygen was determined by “trying and error” method. The coke rate decreases with increase in injectants flow rates. The in-furnace temperature, as a whole, decreases for both practices, which in addition to the reduction of energy requirements of silicon transfer process and reduction of iron oxides, decreases the specific energy necessary. The silicon content in hot metal decreases with increase in pre-reduced fine ore/flux injection rate. Decrease in silicon content is due to basically two mechanisms. One is the decrease in the temperature in and around the raceway with fine injection. And the other is the decrease of the silica activity in the molten slag phase. The silica activity in the molten slag depends strongly of the slag temperature and slag composition. Because the generation rate of SiO gas depends of the silica activity of the molten slag and decrease in silica activity suppresses the generation of SiO, silicon transfer to the hot metal through SiO reduction is suppressed, resulting in decrease of the silicon content in hot metal.

In practice 1, slag volume does not change regardless of pre-reduced fine ore injection rate. When pre-reduced fine ore and flux are injected simultaneously, the slag rate slightly increase with injection rate. Regarding slag basicity, it decreases in practice 1, while the basicity increases in practice 2. For practice 2 the silicon content in hot metal decreases, but flux is basically composed of CaO and MgO. Thus CaO in the final slag increase without a correspondent increase in silica, therefore the slag basicity increases in this practice. The increase in slag volume in practice 2 is mainly due to the flux injection, since the flux charged to the top of the blast furnace was not completely replaced because the primary slag formed in the cohesive zone must have enough fluidity. In Table 7 the amount of direct and indirect reduction is presented. The amount of direct reduc-

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tion increases in practice 1 and 2, respectively. As pre-reduced fine ore is injected through the blast furnace tuyeres, the melted wustite must be reduced in the lower part of the blast furnace. In addition, the temperature of the blast furnace decreases, which in turn, deteriorates the indirect reduction in the stack region. Therefore a larger amount of melted wustite is reduced by direct reduction in the cohesive zone and beneath the cohesive zone.

3.3. In-furnace Status Under Multiple Injection Operation

This section discusses effects of multiple injection on in-furnace distributions of several process variables. Figure 4 shows the predicted temperature distributions of gas phase for the base case and cases with maximum injection rates in two practices. The operation with pre-reduced fine ore injection shows slightly lower temperature distribution. Simultaneous injection of pre-reduced fine ore and flux cools whole furnace, and all isotherms shift downward, except hotter than 2000 °C. In the latter case, high temperature region (higher than 1800 °C) shrinks drastically. This occurs due to the high amount of energy consumed to melt down and reduce the iron oxides in this region. Figure 5 depicts mass flux vectors of hot metal phase. The cohesive zone is drawn with solid lines in the figures. The position of the cohesive zone descends with increase in ore/flux injection rate, and hot metal flow rate beneath the raceway zone increases with injection rate. Higher liquid flow rate under the combustion zone is mainly due to injectants. In addition, solid flow along the cohesive zone in multiple injection case, which is caused by the lower position of cohesion zone, transports iron-bearing materials to the periphery zone. This reduces flow rate in central region and enhances peripheral flow of liquid. This intensified peripheral flow of molten metal maintains the hot metal temperature while lower part of the blast furnace cools, because temperature of this region is still higher than average hot metal temperature.

Figure 6 shows the distributions of molten slag volume fraction. In practice 1, the slag volume fraction increases with injection rate of pre-reduced fine ore. In this case, cohesive zone location is slightly lower than base case, but slag generation region is almost same. However, solid charging rate in practice 1 is higher than base case. Thus more slag stays in the central region of lower part of the blast furnace. On the other hand, solid flow along the cohesive zone takes gangue materials away from the central region, furthermore, flux materials in the charge are reduced in practice 2. Therefore the slag in the central region decreases in this case. In the combustion zone, injected flux materials turn into molten slag and gangue materials transported with the solid flow boost the increase of slag volume fraction beneath the raceway zone. Figure 7 shows the frac-

<table>
<thead>
<tr>
<th></th>
<th>Base (no fine ore)</th>
<th>Fine ore (practice 1)</th>
<th>Fine ore + Flux (practice 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indirect reduction (kg Fe/tm)</td>
<td>931.3</td>
<td>872.2</td>
<td>848.0</td>
</tr>
<tr>
<td>Direct reduction (kg Fe/tm)</td>
<td>4.4</td>
<td>30.2</td>
<td>50.1</td>
</tr>
<tr>
<td>Total (kg Fe/tm)</td>
<td>935.7</td>
<td>939.9</td>
<td>943.1</td>
</tr>
</tbody>
</table>

Obs: The difference between the total iron and the reactions listed above is due to the metallic iron in the pre-reduced fine ore
tional reduction distributions. In practice 1, the fractional reduction curves are shifted down following the isotherms. In practice 2, this phenomenon is more severe and complete reduction is observed in lower positions in the blast furnace. These reduction patterns are closely related with the amount of indirect reduction presented in Table 7.

4. Conclusions

A mathematical model of the blast furnace has been developed which simulates the blast furnace operation under co-injection of pulverized coal, pre-reduced fine ore and flux. The model considers multiphase chemical reactions with rates calculated by kinetic equations. The pulverized phases are separated into two phases (PC and pre-reduced fine ore/flux). The hot metal temperature was kept constant in all cases to examine the effect of multiple injection, while the blast composition and injection conditions were adjusted.

Simulation results have shown that lower silicon content in pig iron can be obtained by means of multiple injection of pulverized coal, pre-reduced fine ore and flux. Moreover, simulated results have shown that the productivity of the blast furnace can be largely increased with this practice.

Nomenclature

- $A$: surface area (m$^2$)
- $C_d$: drag coefficient (—)
- $d_i$: particle diameter ($i$= fine ore/flux or pulverized coal) (m)
- $F_{i,j}$: interaction force in the phase $i$ due to phase $j$ (W/m$^3$)
- $Fr$: Froud number (—)
- $M_j$: molar weight of $j$ species (g/mol)
- $Re$: Reynolds number (—)
- $t$: time (s)
- $u_{i,v}$: phase axial velocity (m/s)
- $V_i$: phase velocity vector (m/s)

Greek symbols

- $G_{\psi,y}$: effective diffusion coefficient for variable $\psi$
- $\epsilon_i$: phase volume fraction (—)
- $\mu$: dynamic viscosity (Pa·s)
- $\rho$: phase density (kg/m$^3$)
- $\phi_i$: shape factor (—)

REFERENCES