Iron ore sintering involves the movement of a flame front down a particulate bed, and a series of physico-chemical reactions over a large temperature range. In the literature simple and more sophisticated iron ore sintering models have been reported. In this paper a more comprehensive numerical model which incorporates most of the significant processes and heat transfer modes proposed in earlier models is given. Therefore, sub-models are available to describe the relationship between airflow rate through the bed and flame front speed, the evaporation and condensation of water ahead of the front, the calcination of fluxes nearer to the front, the reactions that occur in the front and cooling of the bed with the departure of the front. Improvements were made to several areas – such as coke combustion, and the melting and solidification processes – to more accurately quantify the phenomena involved. More recent progress in understanding the fundamentals of sintering from BHP Billiton studies have also been incorporated into the model. To date, twelve sinter pot tests have been used for validation studies. Reasonably good agreement was obtained between predicted and measured results – in areas such as bed temperature profiles and waste gas temperature and compositions. Work is continuing to further improve the model, and broaden the validation work to include other bed temperature profile parameters.

KEY WORDS: iron ore sintering; numerical modeling; melting and solidification; coke combustion; heat and mass transfer.

1. Introduction

Currently, the world produces in excess of one billion tonnes of hot metal per year from ironmaking blast furnaces.1) For most blast furnaces the major iron-bearing feed material is sinter. In the Asia Pacific region sinter constitutes about 80 wt. % of the ferrous charge; therefore the cost and production rate of sinter, and the properties of the formed sinter have a significant impact on the overall economics of steel making. The iron ore sintering process is extremely complicated, involving a large number of inter-related variables. Since the 1950s many studies have been carried out to understand the factors that determine sinter plant performance – usually expressed in terms of productivity, coke requirements and product quality – and the effect of raw material properties (viz., iron ore, flux and adjunct material properties).2–4)

As expected there is a vast amount of knowledge obtained from laboratory studies, many of which involve carefully controlled experiments with one factor changing at a time. Another approach to understand the sintering process is through mathematical modeling. A good mathematical model that captures all the important factors is clearly a very powerful tool as it can be used to rank the importance of the different factors that influence sinter production or coke requirements. There are many mathematical models that describe the sintering process, however due to significant knowledge gaps in the area they incorporate varying levels of empirical relationships. Over the last two decades, BHP Billiton and other research establishments have made significant progress in understanding the fundamentals of iron ore sintering.2,5,6) More recently, Zhejiang University commenced the development of a mathematical sintering model with emphasis on fundamental rather than empirical relationships. BHP Billiton pot tests were carried out to obtain data to validate the model. A specific requirement of the pot test work is to determine the thermal profile histories experienced at the different regions of the sintering bed, to compare with predicted model results. Without information on the heat imparted to a sintering bed by the moving flame front it is not possible to determine the quality of the sinter produced e.g., strength and reducibility.

2. Sinter Models

The mathematical modeling of the iron ore sintering process has received much attention since the 1970s, when Muchi and Higuchi7) proposed the first one dimensional (1-D) model. Fig. 1 is an attempt to explain how the sintering process can be treated as a one or a two dimensional (2-D) process. The top left quadrant shows a side view of a steady
state sintering bed viz., the transformation of the green bed to sinter is shown as a function of strand length and bed height. This is 2-D steady state representation of the process and three distinct zones can be indentified viz., the sintered bed, the high temperature zone and the un-sintered bed. The top right quadrant is a schematic representation of a thin slice of the bed about half way down the sinter strand. A 1-D sintering model can be used to predict bed temperature profiles, gas and solid compositions and flow velocities etc., as the high temperature zone moves down the bed. The bottom right quadrant shows a typical 1-D transient temperature profile at a certain time after the commencement of sintering. Numerous 1-D representations of the bed at different times can be collated to obtain a 2-D steady state representation of the sintering process on a strand and this is shown in the bottom left quadrant. The 1-D and 2-D representations are equivalent when lateral changes-across the width and length of the strand-are neglected. For this reason, with a few exceptions,8,9) most of the previous sintering models are one dimensional.10–16)

Young16) developed a 1-D mathematical model which studied in detail the heat and mass transfer processes in a sintering bed. With the formation of melt, changes in heat transfer were taken into consideration by simply modifying the specific heat of solid. A shrinking core model was used to describe the combustion of coke and calcination of limestone. The product of coke combustion was assumed to be only CO2. This is a simple representation of the coke combustion mechanism, and neglects the possible formation of CO at high temperatures.

Yoshinaga et al.15) investigated the transient sintering process in a batch sintering machine and a steady state process on a Dwight-Lloyd sintering machine. To define the relationship between pressure drop and gas flow rate in the Ergun equation. A mechanistic three-step drying process was adopted in this model.

A more comprehensive sintering model is presented by Cumming et al.10) The shrinkage of the sinter bed was described by a novel shrinkage factor calculated from a differential equation, and eight ore-related reactions. To date this is the most comprehensive consideration of the effect of ore properties on sintering reactions. Major shrinkage of the bed was assumed to be caused by the presence of melt, and has been termed slumping. In modeling heat transfer only convection was taken into account; both conduction and radiation were omitted.

Patisson et al.12) divided the sintering bed into four zones and modeled the heat transfer process using experimentally determined convective heat transfer coefficient. In particular, the drying and condensation mechanisms were investigated in detail.12,17) To quantify the rate of melt formation a new approach involving the use of phase diagrams to determine the melt fraction was proposed. However, a simplistic coke combustion model incorporating a correction factor to account for incomplete combustion was used. The calcination requirements of fluxes were not included in their model. As flux calcination can consume approximately 20% of the heat released by coke combustion, neglecting this reaction would lead to large modeling errors.

Probably the most recent sintering model is that developed by Yang et al.14,18) This model includes heat transfer by radiation using the two-flux model, which is to the best of our knowledge the first model to explicitly incorporate heat transfer modes other than convection. However, it was shown that the contributions of radiation are small compared to convection. Measurements of temperature, gas composition were made, and model predictions gave reasonable agreement with the measured values. However, the momentum equation was not included in the model formulations. Neither were the melting and solidification process considered, and this is acknowledged by the authors.14)
Although currently available models have contributed significantly to our understanding of iron ore sintering, they can be improved in several aspects. Firstly, a more comprehensive mathematical formulation should include material mass and species, and momentum and energy conservations. Secondly, there is a need for a more rigorous consideration of the melting and solidification processes, and in particular their effects on heat and mass transfer. Finally, current treatment of coke combustion, which is one of the most significant reactions in sintering, is very simplistic and could be improved.

This paper reports a new mathematical formulation of the iron ore sintering process. Material mass and species, and momentum and energy conservations for both gas and solid phases are included. To solve the momentum equation for gas flow, the relationship between pressure and velocity is quantified using the SIMPLE algorithm.\(^\text{19}\) A simplified gas flow, the relationship between pressure and velocity is used.

### 3.1. Assumptions

The major assumptions used in the formulation of the model are:

A. Iron ore sintering is considered a 1-D transient process; the lateral transfer of heat and mass across the bed being negligible.

B. The continuum of the gas (O\(_2\), CO\(_2\), CO, H\(_2\)O and N\(_2\)) and solid (coke, limestone, lime, dolomite, magnesia, water, hematite and magnetite) phases; with the gases flowing through a stationary bed of solids and melts are stationary and the ideal gas law obeyed.

C. Eight equations can define the gaseous, gas-solid and solid phase reactions (listed below under I – VIII) and drying and condensation can be considered as a gas-solid reactions.

\[
\begin{align*}
\text{Coke Oxidation} & : 2C + O_2 \rightarrow 2CO \\
\text{CO Oxidation} & : 2CO + O_2 \rightarrow 2CO_2 \\
\text{Limestone Calcination} & : CaCO_3 \rightarrow CaO + CO_2 \\
\text{Dolomite Calcination} & : CaMg(CO_3)_2 \rightarrow CaO + MgO + 2CO_2 \\
\text{Drying/Condensation} & : H_2O(l) \leftrightarrow H_2O(g) \\
\text{Melting} & : \text{Solid Mixture} \rightarrow \text{Melt} \\
\text{Solidification} & : \text{Melt} \rightarrow \text{Precipitated Minerals and Phases}
\end{align*}
\]

D. Coke, limestone, dolomite and iron ore particles have characteristic size distributions; in a sinter mix the layering of fines onto the surfaces of larger particles produces granules with a pre-defined size distribution.

E. There are no temperature variations within granules because of their moderate thermal conductivity (effective thermal conductivity estimated to vary from 7.86 to 2.61 W m\(^{-1}\) K\(^{-1}\) at temperatures of 25 to 1400°C).

F. Due to unavailable information and experimental data in the literature, bed shrinkage and its effect on gas flow, pressure drop and heat transfer are ignored.

G. The formation of melt inevitably results in material coalescence, which decreases the effectiveness of convective heat transfer.

H. Due to unavailable information and experimental data in the literature, bed shrinkage and its effect on gas flow, pressure drop and heat transfer are ignored.

A schematic representation of the components of the model is shown in Fig. 2. Further details on the different parts of the model are given below.

### 3.2. Governing Equations

Based on the assumptions, the governing equations for material mass and species, energy and momentum conservations for the gas phase can be written as follows. All the notations are listed in Table 1. \(\rho_g\) is true gas density.

**Gas phase mass conservation:**

\[
\frac{\partial}{\partial t}(\rho_g \cdot \rho_s) + \frac{\partial}{\partial y} \left( \rho_g \cdot \rho_s \cdot u_g \right) = \sum_{i=1}^{\text{VIII}} \sum_{k=1}^{\text{E}} \dot{m}_{i,k} 
\]

**Gas phase species \(i\) conservation (\(i = O_2, CO_2, CO, H_2O\) and N\(_2\))**:

\[
\frac{\partial}{\partial t} (\rho_g \cdot Y_i) + \frac{\partial}{\partial y} (\rho_g \cdot \rho_s \cdot u_g \cdot Y_i) = \sum_{i=1}^{\text{VIII}} \sum_{k=1}^{\text{E}} \dot{m}_{i,k} 
\]

**Gas phase energy conservation:**

\[
\frac{\partial}{\partial t} (\rho_g \cdot \varepsilon) + \frac{\partial}{\partial y} (\rho_g \cdot \rho_s \cdot u_g \cdot \varepsilon) = h_{\text{con}} \cdot A_i \cdot (T_g - T_e) + \sum_{i=1}^{\text{VIII}} \sum_{k=1}^{\text{E}} \dot{q}_{i,k} 
\]

**Gas phase momentum conservation:**

\[
\frac{\partial}{\partial t} (\rho_g \cdot \rho_s \cdot u_g) + \frac{\partial}{\partial y} (\rho_g \cdot \rho_s \cdot u_g \cdot u_g) = -\varepsilon \cdot \frac{\partial P}{\partial y} - F_v 
\]
For the solid phase, the governing equations for mass, species and energy conservations can be expressed as follows. Solid phase mass conservation:

$$\frac{\partial \rho_s}{\partial t} = -\sum_{k=1}^{VIII} \sum_{j} \dot{m}_{j,k}$$ .......................... (5)

Solid phase species j conservation (j = coke, limestone, dolomite, magnesia, lime, water, hematite and magnetite):

$$\frac{\partial}{\partial t} \left[ Y_j \cdot \rho_s \right] = \sum_{k=1}^{VIII} \sum_{j} \dot{m}_{j,k}$$ .......................... (6)

Solid phase energy conservation:

$$\frac{\partial}{\partial t} \left[ \rho_s \cdot h_s \right] = \frac{\partial}{\partial y} \left[ k_{eff} \frac{\partial h_s}{\partial y} \right] + h_{com} \cdot A_C \cdot (T_s - T_{eq}) + \sum_{k=1}^{VIII} \sum_{j} \dot{q}_{j,k}$$ .......................... (7)

The source term \(\sum_{k=1}^{VIII} \sum_{j} \dot{m}_{j,k}\) in Eq. (1) represents the mass production rate of gas due to reactions I–VIII. For the gas phase, the equation of state is \(P = 1000 \rho_s \cdot R_s \cdot T_s \cdot \sum_{y} Y_y \cdot W_y\). In Eq. (4), \(F_r\) represents the resistance to gas flow in the porous solid matrix, which is evaluated from the Ergun equation.20

In Eqs. (3) and (7), the source terms \(\sum_{k=1}^{VIII} \sum_{j} \dot{m}_{j,k}\) and \(\sum_{k=1}^{VIII} \sum_{j} \dot{q}_{j,k}\) represent the heats generated/consumed from reactions I–VIII for gas and solid phases, respectively.

### 3.3. Key Sub Models

The key sub-models include coke oxidation, CO oxidation, limestone calcination, dolomite calcination, drying and condensation, melting and solidification, magnetite oxidation, heat and mass transfer. These are described in detail in the following paragraphs.

#### 3.3.1. Coke Oxidation

Carbon can react with oxygen to form CO or CO₂ or both. However, it is generally agreed that at temperatures greater than 1 000 K, CO is the main product.21–24 Therefore, reaction I is the assumed coke oxidation reaction. According to Hobbs et al.,25 coke oxidation rate per unit bed volume can be written as:

$$R_{\text{coke}} = \frac{2 \cdot A_C \cdot W_s \cdot C_{O^*}}{k_c + \frac{1}{k_{film}} + \frac{1}{k_{coating}}}$$ .......................... (8)

where, \(k_c\) is the reaction rate constant, \(k_{film}\) the film mass transfer coefficient, \(k_{coating}\) the mass transfer coefficient through the coating solids (fluxes, iron ore and return fines) and the developing ash layer. The kinetic data used are from Fu et al.25 The un-reacted core diameter \(d_{s,0}\) is calculated from mass balance by assuming spherical particles and constant solid density,26 thus \(d_{s,0} = d_{s,0} \cdot (m_t / m_{s,0})^{1/3}\) and the instantaneous diameter of the coke particle (with ash) is:

$$d_s = \left[ 1 - 3 X_{ash} \right] d_{s,0} + \frac{X_{ash} \cdot d_{s,0}}{N_{ash}}$$ ................. (9)

where, \(d_{s,0}, d_{s,0}\) and \(m_{s,0}\) are initial coke core diameter, un-reacted core diameter and mass of fixed carbon respectively, \(X_{ash}\) is the mass fraction of ash in the coke.

#### 3.3.2. CO Oxidation

The CO produced from coke is oxidized in the gas phase according to reaction II, and the oxidation rate is:

$$R_{\text{CO}} = 3.25 \cdot 10^{-7} \cdot C_{CO} \cdot C_{O^*} \cdot C_{H_{2,0}} \cdot \exp\left(-\frac{15 098}{T_s}\right)$$ ....... (10)

#### 3.3.3. Limestone Calcination

Limestone decomposes when its temperature reaches a certain value and the CO₂ concentration in bulk gas is less than the equilibrium concentration of CO₂. According to Young,16 the limestone calcination reaction rate is:

$$R_{\text{calc}} = \frac{A_{\text{l,calc}} \cdot W_{ls} \cdot (C_{CO_{2}}^0 - C_{CO_{2}})}{Sh_{ls} \cdot D_{CO_{2}} + \frac{d_{ls,0} \cdot (d_{ls,0} - d_{ls})}{d_{ls} \cdot D_s} + \frac{C_{CO_{2}}^0 \cdot d_{ls,0}}{k_l}}$$ ................. (11)

where, \(C_{CO_{2}}^0 = \frac{K^2}{R \cdot T_{eq} \cdot 1000}, \quad K^2 = 101.325 \cdot \exp(7.0099 - \frac{8205.4}{T_s})\),

$$\frac{\theta_{ash} \cdot D_{CO_{2}}}{\tau} = \frac{1.52 \cdot 10^{-3} \cdot \exp\left(-\frac{20 143.4}{T_s}\right)}{T_s}$$ .......................... (12)

#### 3.3.4. Dolomite Calcination

In addition to limestone, dolomite is also an important source of magnesia for many sinter mixes and, therefore, should be included in the model. Hartman et al.28 studied the calcination of dolomite at moderate temperatures using a TGA and obtained an expression for calcination rate as a function of temperature and conversion:

$$\frac{dX}{dt} = 1.628 \cdot 10^{-7} \cdot \exp\left(-190.67 \cdot 10^3 / R_s T_s\right) \cdot (1 - X)^{0.4043}$$ .......................... (12)

where \(X\) is the conversion of dolomite.
3.3.5. Drying and Condensation

Drying of solid is usually characterized using two stages, a constant-rate stage followed by a falling-rate stage.30) The two stages are separated by a critical solid moisture content \( M_{cr} \). In the present study, both drying and condensation are assumed to be controlled only by mass transfer. Drying occurs when the saturation vapor pressure \( P_{H2O}^s \) is greater than the partial pressure of vapor in the bulk gas \( P_{H2O} \); when \( P_{H2O} < P_{H2O}^s \), condensation occurs. The drying rate \( R_{drying} \) and condensation rate \( R_{conden} \) are given by:

\[
R_{drying} = \gamma \cdot k_{H2O} \cdot W_{H2O} \cdot A_\alpha \cdot (P_{H2O}^s - P_{H2O}) / R_T \quad \text{(13)}
\]

where,

\[
\gamma = \begin{cases} 
1 & , \quad \psi > 1 \\
1 - (1 - \psi) \cdot (1 - 1.796 \cdot \psi + 1.0593 \cdot \psi^2) & , \quad \psi \leq 1
\end{cases}
\]

\[
\psi = M_{H2O} / M_{cr}
\]

\[
R_{conden} = k_{H2O} \cdot W_{H2O} \cdot A_\alpha \cdot (P_{H2O} - P_{H2O}^s) / R_T \quad \text{(14)}
\]

where, \( k_{H2O} \) is the mass transfer coefficient, \( \gamma \) is the polynomial correlation of the characteristic drying curve for iron ore particles,13) the critical solid moisture content \( M_{cr} = 5\% \).17)

3.3.6. Melting and Solidification

Melting and solidification are significant phenomena in sintering. Actual melting and solidification processes are very complicated.30) Melt formation during sintering has been conceptually viewed as comprised of two stages viz., primary melt formation followed by nuclear particle assimilation. The rate of assimilation would be determined by primary melt formation followed by nuclear particle assimilation; melting initiation can be viewed as an inverse process of the melting, and solidification can be expressed as:

\[
\tau \cdot D_{O_2} \cdot N_{MO} \cdot W_m \cdot (C_{O_2} - C_{O_2}^*)
\]

where, \( \tau \) is the tortuosity of the structure of the hematite formed. A fixed value of 2.5 was adopted for \( \tau \) according to the experimental determinations by Papanastassiou et al.13) \( N_{MO} \) is the number density of magnetic particles.

3.3.7. Magnetite Oxidation

For sinter mixes containing magnetite, the oxidizing atmosphere will cause some of the magnetite present to oxidize to hematite. This is an exothermic reaction and for blends containing high levels of hematite this additional heat generated must be considered. The reaction rate can be expressed as:34)

\[
R_{M-H} = \frac{4\pi \cdot d_{O_2}^2 \cdot N_{MO} \cdot W_m \cdot (C_{O_2} - C_{O_2}^*)}{Sh \cdot D_{O_2} \cdot (d_{M} - d_{MO}) / \left( d_{MO} \cdot D_{HP} \right)} + \frac{1}{d_{MO} \cdot D_{HP} \cdot k_{M-H}}
\]

where, \( C_{O_2}^* = 101325 \cdot K_{M-H} / (R_H \cdot T_s \cdot 1000) \), \( K_{M-H} = \exp(-706499.22 / T + 40.69) \), \( D_{HP} = \frac{D_{O_2} \cdot e_{HP}}{\tau_{HP}} \), \( k_{M-H} = 3 \cdot 10^{-7} \cdot \exp(-6000 / T_s) \).

\( \tau_{HP} \) is the tortuosity of the structure of the hematite formed. A fixed value of 2.5 was adopted for \( \tau_{HP} \) according to the experimental determinations by Papanastassiou et al.35) \( N_{MO} \) is the number density of magnetic particles.

3.3.8. Heat and Mass Transfer

As shown in Fig. 1, significant bed structural transformations occur with the arrival and passing of the flame front. This transformation will influence heat and mass transfer in the bed. Since the major cause of bed transformation is believed to be the formation of melt and its subsequent solidification,27) it seems reasonable to take these changes into account at melting and solidification. In this study, this is done by altering the value of channeling factor \( \eta \), in the bed. As outlined in the model assumptions, the generation

## Table 2. Latent heats of melting and solidification derived from the literature and the values adopted in the present study.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Latent heat of melting (MJ/kg)</th>
<th>Latent heat of solidification (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ramos et al.24)</td>
<td>0.2543</td>
<td>Not available</td>
</tr>
<tr>
<td>Toda et al.27)</td>
<td>0.234–0.275</td>
<td>Not available</td>
</tr>
<tr>
<td>Young28)</td>
<td>0.254</td>
<td>Not available</td>
</tr>
<tr>
<td>Ellis et al.25)</td>
<td>0.2625</td>
<td>0.117</td>
</tr>
<tr>
<td>Present study</td>
<td>0.254</td>
<td>0.117</td>
</tr>
</tbody>
</table>

An average value of 0.254 MJ/kg is used in the present model. For the heat of solidification, the only data available gives a value of 0.117 MJ/kg and this value is used in the present model.

After the melt fraction \( \beta \) is determined, the melting and solidification heat can be given as:

\[
\dot{q}_{L,M} = -\frac{\partial}{\partial t}(\beta \cdot L \cdot \rho_b) \quad \text{(16)}
\]

where \( \dot{q}_{L,M} \) is used in the source terms of Eqs. (3) and (7) to account for melting and solidification heats; \( L \) is the latent heat and subscripts \( m \) and \( s \) are used to denote the latent heat at melting and solidification; \( \rho_b \) is the bulk density of the bed.
of melts can reduce convection heat transfer. In preference to the Ranz correlation,\textsuperscript{36} the Kunii-Suzuki correlation\textsuperscript{37} is adopted for modeling convection heat transfer in sintering, because it includes the channeling factor $\eta$, which can be adjusted according to the melt fraction $\beta$ to account for the phase change effect. The Kunii-Suzuki correlation is given by:\textsuperscript{37}

\begin{equation}
\eta = \eta(\beta) \quad \text{in present work, } \eta \text{ is assumed to change linearly with } \beta \text{ from an initial value of } \eta_{\text{ini}} = 1 \text{ (corresponding to the green bed) to a final value } \eta_{\text{end}}. \text{ The value of } \eta_{\text{end}} \text{ is determined empirically. Cumming et al.\textsuperscript{40} has given expressions of how these two variables would depend on temperature and they are used in exponentially determined profiles and is therefore adopted. For mass transfer in the sintering bed, the Kunii-Suzuki correlation\textsuperscript{37} is used.}
\end{equation}

3.3.9. Radiation and Conduction

Radiation and conduction play a relatively minor role in heat transfer in a sintering bed compared to convection. It has been proposed that radiation and conduction in the packed bed can be modeled using an effective thermal conductivity term $k_{s,\text{eff}}$.

\begin{equation}
k_{s,\text{eff}} = (1-\varepsilon)k_s + 4 \cdot \Sigma \cdot \varepsilon \cdot \rho \cdot d_p \cdot T_s \quad \text{for gases (O}_2, \text{CO, CO}_2, \text{H}_2\text{O and N}_2) \text{ as functions of temperature are obtained from Ref.\textsuperscript{41}. Gas dynamic viscosity is assumed to be the same as that of dry air\textsuperscript{42} and is obtained from the work of Turms.\textsuperscript{42}}
\end{equation}

3.3.10. Physical Properties

The specific heat and thermal conductivity of all ferrous materials are assumed to be the same as that of hematite. Donskoi et al.\textsuperscript{39} has given expressions of how these two variables would depend on temperature and they are used in this model. The specific heat of other solids (limestone, lime and coke) and water are adopted from Yang.\textsuperscript{43} The specific heat of gases (O\textsubscript{2}, CO, CO\textsubscript{2}, H\textsubscript{2}O and N\textsubscript{2}) as functions of temperature are obtained from Ref.\textsuperscript{44}. Gas dynamic viscosity is assumed to be the same as that of dry air\textsuperscript{40} and is obtained from the work of Turms.\textsuperscript{42}

3.3.11. Initial and Boundary Conditions

The experimental conditions used in the sinter pot tests are used to define the initial and boundary conditions, which are: during ignition, the gas temperature is set to the ignition temperature for 1.5 min at the bed top and after ignition the inlet gas temperature is set to the ambient temperature. All gas species mass fractions are specified at the inlet. At the outlet, the gradient of all gas species concentrations is set as zero. Inlet gas velocity is set to values determined from the sinter tests. The suction value used in the pot test defines the outlet pressure.

To solve the above partial differential equations, the finite volume method enunciated by Patankar\textsuperscript{39} is employed. In each time step, the gas velocity and gas pressure, gas and solid temperatures and concentrations are computed in iterations until a certain termination criteria is satisfied. Then the iteration is terminated in the current time step and the procedure is repeated for the next time step. In solving the momentum equation for gas flow, SIMPLE algorithm\textsuperscript{19} is used to treat the pressure-velocity relationship.

4. Experimental

The commercial sintering process is widely simulated in laboratories around the world using a sinter pot. A large number of systematic experiments have been carried out by BHP Billiton on their sinter pot and the results have been made available to Zhejiang University to enable the developed model to be validated.

4.1. Pilot-scale Plant

A detailed description of the BHP Billiton pilot-scale sinter plant has been given.\textsuperscript{43} The reader is asked to refer to this document for details. The standard BHP Billiton sinter pot has a cross sectional area 0.09 m\textsuperscript{2} and height 600 mm. Three thermocouples are mounted at 100, 300 and 500 mm down bed and one in the wind box. An air hood is placed on the top of the pot to regulate air flow and a hot wire anemometer is installed in the hood to measure the inlet airflow rate. The suction in the wind box is created by the fan. A gas burner is used to ignite the top of the bed.

4.2. Procedures and Measurements

The sinter mix was granulated and then charged into pot. The surface of the formed bed was ignited for 1.5 min using a gas burner. This was done at a fixed suction of 6 kPa. After ignition, the suction was increased to the specified (sintering suction) value and maintained until the end of sintering. The produced sinter was then stabilized by dropping and then analyzed. For each test, bed temperature, waste gas temperature and composition, wind box suction and inlet airflow rate were continuously monitored during sintering. Twelve sinter pot tests-conducted using varying conditions e.g., applied suction, coke in mix, mix moisture and limestone level-were used to validate the present model. In this paper, only the bed temperature profiles from three tests (I, II and III) are shown.

5. Results and Discussion

Typical profiles of suction, inlet airflow rate and waste gas temperature as measured in the sinter pot test, together with the simulated waste gas temperature profile are given in Fig. 3. The applied suction was low 6 kPa during ignition, but increased to 16 kPa after ignition and maintained at this value until the end of sintering i.e., after sinter cooling. The measured waste gas temperature was at ambient temperature for around 2 min and then raised to a steady-state waste gas temperature (SSWGT) of around 60°C. This phenomenon was observed in all the sinter pot tests\textsuperscript{39} and can be simulated by the present model, as shown in Fig. 3. The simulated temperature represents the gas temperature at the bottom of the bed while the measured temperature is that of waste gas in the wind box – which means that they are not directly comparable. The magnitudes of the two temperatures are also different near burn-through; however, they are compa-
The comparisons of maximum bed temperature and sintering time between the 12 measured and simulated cases are shown in Fig. 4. Good agreements are achieved for both sintering time and maximum bed temperature, which indicates the validity of the present model. The sintering time is found to be highly dependent on the inlet airflow rate or suction. While the bed temperature can be affected by a number of factors, e.g., airflow rate or suction, levels of coke, fluxes and moisture.

At the three depths-100, 300 and 500 mm down bed-temperatures were recorded by inserted thermocouples. Waste gas in the wind box is also sampled for analysis. Figure 5 shows comparisons between simulated and measured bed temperature and waste gas composition for three Tests I, II and III (the magnitude of inlet airflow rate for the three tests were: I > II > III, while other parameters for the tests were similar). Good agreements are observed. Filled and open symbols are used to show predicted and measured results respectively. The predicted temperature peaks appear slightly earlier than the corresponding measured ones especially in the upper bed. This may be explained by the omission of bed shrinkage in the model. Test III has a wider temperature profile and a longer sintering time than Test I and II because of its lower inlet airflow rate. This implies that the sinter produced from Test III would have a higher strength but lower productivity than the other two cases and experimental results confirm this. The predicted O₂, CO and CO₂ compositions all agree reasonably well with measured data.

The 1-D transient sintering process can be converted into the 2-D steady process in the Cartesian coordinate system when the abscissa uses the time and ordinate uses bed height. Predicted typical 2-D results for bed temperature and maximum melt fraction are shown in Fig. 6 for an assumed strand speed of 2 m/min. It can be observed that as sintering progresses maximum bed temperature increases and the width of the high temperature zone widens. The melt fraction present in the lower bed is observed to be higher than that in the upper bed, and this is observed in practice. The results imply that the sinter produced from the upper bed is weaker than that from the lower bed.

With the present melting and solidification model, melt generation in the bed can be simulated. Figure 7 shows the predicted melting and solidification heats and melt fraction as functions of time at mid-bed position under Test I conditions. With the arrival of the flame front, bed temperature increases to above 1 100°C and the assimilation of solid into melt commences. This is an endothermic reaction and involves the breaking down of solid lattice structure. The burning out of coke particles coincides with the departure of the flame front and the solids start to lose heat to the incoming stream of cooler air. During solidification, different minerals and phases precipitate out and heat is also released. The shaded areas in Fig. 7 indicate the total heat absorbed/released during the melting/solidification process. It is seen that the total heat absorbed during melting is larger than the heat released during solidification, which means that only part of the latent heat can be recovered. Although the present melting and solidification model can quantify reaction heats and melt fraction as functions of time, it still involves some empiricism and only takes into account the thermodynamic aspects of melting and solidification. A

rable before burn-through. Their small rise at approximately 2 minutes indicates the disappearance of the humidified zone in the beds. In the present case, the simulated SSWGT is 51°C, which is not too different to the measured value of 61°C.
kinetic model will be considered in future work.

Figure 8 shows the simulated variations in pressure gradient and gas temperature at 5, 9, 13 and 17 min after ignition for Test I. It is seen that in the sintered zone, the pressure gradient is generally lower than that in both the high temperature and un-sintered zones. It can also be seen that the largest pressure gradient or pressure drop is always found at the high temperature zone. This explains the observed significant decrease in bed permeability on igniting the bed in the sinter pot. Because of the importance of the high temperature zone, changes in its thickness and temperature can have a large impact on the permeability of the sintering bed.
6. Conclusions

This paper reports a new numerical model of the iron ore sintering process. The developed ZJU-BHP Billiton iron ore sintering model considers most of the significant phenomena and processes in sintering including: convective heat transfer, the combustion of coke particles, the calcinations of limestone and dolomite, bed drying and the subsequent condensation of this water in the lower bed, and gas flow and pressure relationships in the bed. Many of these have not been considered in currently available models. In addition, this model also includes radiative and conductive heat transfer, and melting and solidification in the flame front. To validate the model, results from twelve carefully controlled sinter pot tests were used. There was good agreement in the areas of bed temperature, gas composition and sintering time. The model also predicts a reasonable value of the steady-state waste gas temperature—obtained not long after ignition and remains reasonably constant until close to burn-through. This paper also shows that the developed 1-D transient model results can be easily converted into a 2-D steady state representation of sintering on a strand. The good comparison obtained between model-predicted and pot tests results in the areas of bed temperatures and melt generation—suggest that current considerations of the melting and solidification process are acceptable. As expected the model predicts minor increases in pressure gradient in the sintered zone, rising to a peak value in the high temperature zone, and then dropping off in the un-sintered bed. In comparison to convection, conduction and radiation have less significant effects on the heat transfer in the sintering bed. This is mainly due to the fact that the thermal conductivity and size of the bed material are not large enough. Work is continuing to further improve the applicability of the current model, include a sub-model to predict productivity and improve the melting and solidification sub-model. The validation work also needs to be broadened to include other bed temperature profile parameters.

Acknowledgments

The financial support for this work has been provided by BHP Billiton and this is gratefully acknowledged. The authors are also grateful to BHP Billiton for allowing them to use sinter pot test results obtained by Newcastle Technology Centre in Australia. Financial support from National Basic Research Program of China (2009CB218902), a Foundation for the Author of National Excellent Doctoral Dissertation of China (200747), the Program of Introducing Talents of Discipline to University (B08026), and Key Technologies R&D Program of China (2011BA04B01) for Prof. Zhou is also gratefully acknowledged.

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