Model Predictions of Important Bed and Gas Properties during Iron Ore Sintering

Hao ZHOU,1)* Jia Pei ZHAO,1) Chin Eng LOO,2) Benjamin George ELLIS3) and Ke Fa CEN1)

1) State Key Laboratory of Clean Energy Utilization, Institute for Thermal Power Engineering, Zhejiang University, Hangzhou, 310027 China. 2) Centre for Ironmaking Materials Research, Discipline of Chemical Engineering, School of Engineering, Faculty of Engineering & Built Environment, The University of Newcastle, Callaghan, NSW, 2308 Australia. 3) BHP Billiton, Shanghai, 200021 China.

(Received on May 24, 2012; accepted on August 6, 2012)

A new numerical iron ore sintering model was developed recently. It takes into account most of the significant physico-chemical processes in sintering. In this study results from the model are compared with experimental results from twenty five sinter pot tests. Results indicate that the model can simulate the iron ore sintering process, as reasonable correlations between predicted and measured results were obtained in many areas. The good comparisons also indicate that the key sub-models, which have significant effects on results, viz., coke combustion, fluxes calcination, drying and condensation as well as heat and mass transfer, describe the sub-processes well. The phenomena of steady-state waste gas composition (SSWGC) and steady-state waste gas temperature (SSWGT) were simulated and analyzed by the model. A total of nine important input variables were identified and their influence on sintering time and three critical parameters which determine heat transfer during sintering were considered in the sensitivity studies. Results showed that bed bulk density, solid and gas thermal capacities, coke level and diameter and post-ignition airflow rate have the greatest influences on sintering time and the temperature profile parameters. This paper also gives suggestions on how the model can be improved.

KEY WORDS: iron ore sintering model; model validation; flame front speed; temperature profiles; sensitivity analysis.

1. Introduction

In the Asia Pacific region, iron ore sinter is the most important ferrous material fed to blast furnaces.1) Since the 1950s, significant efforts have been devoted to understand the sintering process.2–8) Notwithstanding, more work is still necessary because the sintering process is extremely complex. Commercial, pilot and laboratory scale experimental studies have provided a vast amount of information on the factors that determine the efficiency of the process and the influence of ore blends. At the same time, mathematical models have also been developed to predict the effect of changes in operations conditions on the sinter machine performance.8–12) A useful sintering model is one that can provide information on which are the most important variables influencing the important performance indicators i.e., sinter quality, production rate and energy requirements. A superior model can, in addition, assist with the quantification and optimization of process variables e.g., mix moisture of the sinter mix or the size of coke particles.13) Changing the method used to feed the granulated mix onto the sinter strand - aimed at enhancing material segregation and improving green bed permeability – will alter the distribution of particle types and sizes down a sintering bed. Changes in both these areas will have an impact on the temperature at which melts are generated, the sintering reactions, the chemical composition of the melts, the combustion behavior of the coke particles and bed temperature distribution. The fact that these changes do not occur in isolation but influence each other adds further complication, and makes experimental investigation of the fundamental factors controlling the sintering process very difficult. Iron ore sintering models have some advantage in this area because they can decouple some of the intrinsically linked factors.

This paper reports further studies carried out on a newly developed one-dimensional iron ore sintering model, termed the ZJU-BHP Billiton model.14) Results of the model have been tested against some sinter pot test results but a more rigorous examination of the capability of the model is clearly necessary. The main area of focus is the ability of the model to predict bed temperature profiles with the arrival and departure of the flame front. The amount of heat transferred to the sinter mix in the flame front has a controlling influence on sinter quality. The important parameters influencing the total amount of heat transferred are: flame front

* Corresponding author; E-mail: zhouhao@cmee.zju.edu.cn
DOI: http://dx.doi.org/10.2355/isijinternational.52.2168

© 2012 ISIJ
speed, maximum temperature, residence time at greater than 1100°C (solid-liquid reactions commences at around this temperature), enclosed area > 1100°C (product of time and temperature and reflects the total amount of heat transferred during the solid-liquid reaction period). As the model also incorporates a description of coke particle combustion, predicted carbon monoxide and carbon dioxide contents of the waste gases can also be studied. Waste gas temperature during sintering is another variable generated by the model. Studies have shown that it should remain virtually unchanged at around 55°C until towards the end of sintering. The final area of study involves ranking the factors that influence the temperature profile parameters. Most of the pot test results used in this study have been reported in a recent paper by Loo et al..

2. Modeling and Experimental Work

2.1. The Model

The model incorporates most of the significant processes and all heat transfer modes in an iron ore sintering bed. Radiation, convection and conduction, coke combustion, limestone and dolomite calcination, melting and solidification, moisture drying and condensation, as well as bed structural change and gas flow were considered. A simplified melting and solidification model was developed and coupled to convection heat transfer. Compared with earlier models, improvements were made to a number of areas, e.g., coke combustion, dolomite calcination and the melting and solidification processes. To predict the transient distributions of solid and gas temperatures, gas velocity, gas compositions and gas pressure throughout the bed, eighteen equations were numerically solved for the relevant variables. Four types of partial differential equations (PDEs) governing mass, energy, momentum and species conservations for both solids and gases were numerically solved. The governing equations are:

\[ \frac{\partial}{\partial t}(\varepsilon \cdot \rho \cdot \phi) + \frac{\partial}{\partial y}(\varepsilon \cdot \rho \cdot u \cdot \phi) = \frac{\partial}{\partial y} \left( \Gamma \cdot \frac{\partial \phi}{\partial y} \right) + S_\phi \quad \ldots \quad (1) \]

where, the general variable \( \phi \) can be mass, velocity, enthalpy, etc., for different governing equations, \( \Gamma \) is the diffusion coefficient and \( S_\phi \) is the source term.

For this work the inputs into the model are obtained from the sinter pot tests. Airflow rate after ignition, the composition of the sinter mix including the weight of coke and limestone, and bed ignition temperature and time were some important information required as model inputs. For every position down the entire height of the bed, the model is capable of predicting gas and bed properties as functions of time.

2.2. Experimental Program

All experimental pot test data used in this study were conducted at BHP Billiton's Newcastle Technology Centre. These sinter pot tests were carefully carried out to ensure that airflow, temperature and gas composition were determined as accurately as possible.

To ensure accurate measurement of airflow rate, a novel technique was developed to reduce the airflow around the walls of the sinter pot. This technique has been shown to enable the formation of stronger sinter around the walls and at the same time reduce air leakage at the walls - thereby improving airflow rate measurement. For each test, the thermal conditions down a sintering bed were determined using three type R thermocouples inserted into the pot. The temperature-time profiles recorded by these thermocouples are simply termed temperature profiles. A fourth thermocouple was installed in the wind box to measure the waste gas temperature. Waste gas sampling and analysis was carried out using the Gasmet DX-4000 gas analyzer with Fourier transform infrared (FTIR) spectroscopy. Gases including CO, CO₂, CH₄, NO, N₂O and SO₂ were measured in the test. This data provides information on the combustion efficiency of coke particles and pollutant emitted from the test. Detailed descriptions of the procedures have been published.

In this study, the results from 25 sinter pot tests are considered, of which 23 sets of the results have been reported by Loo et al. The 25 tests selected cover a wide range of operating parameters (e.g., fuel rates of 52–68 kg t⁻¹, airflow rates of 65–190 kg m⁻³) to fully test the ability of the model to predict significant changes in operating parameters.
3. Results

In this section, the model predictions of bed temperature profiles will be tested against measured bed temperature profiles, as obtained using thermocouples. In particular, the region of the temperature profile where sintering reactions occur is compared quantitatively and the parameters used are maximum temperature, residence time > 1100°C and enclosed area > 1100°C. From the positions of the temperature profiles as a function of time, flame front speed can be extracted for comparison. The predicted and measured properties of the waste gas were also compared.

3.1. Bed Temperature Profiles

The bed temperatures for each sinter pot test were recorded by thermocouples inserted into the sinter pot at 100, 300 and 500 mm from top of the bed. A typical example of a set of measured and the corresponding predicted bed temperature profiles is shown in Fig. 2. It is seen that the predicted and measured results compare well, with both profiles broadening and the maximum temperature increasing down a sintering bed. Some comparisons are not so good due, in part, to difficulties in obtaining reliable bed temperature profiles and this has been discussed.\(^\text{16}\)

The increase of maximum bed temperature and the broadening of the temperature profile down the bed are mainly attributed to the preheating of the gases by the hot sinter in the upper bed. In all the simulations, the highest bed temperatures were always recorded in the lower bed. However, such good comparisons were not obtained in every case. As explained by Loo et al.,\(^\text{16}\) one reason for this is that temperature measurement in the sinter pot is difficult because it depends strongly on local airflow rate around the thermocouple tip and how far the tip is away from particles undergoing exothermic or endothermic reactions.

Loo et al.\(^\text{16}\) also discussed the importance of three temperature profile parameters that can be derived from the sintering temperature profile. These parameters are defined in Fig. 3 and are considered to strongly influence sinter quality. The first parameter is the maximum temperature. The second is the residence time at above 1100°C (or residence time for simplicity). The third is the area enclosed by temperature profile and the \(y = 1100°C\) line (or enclosed area for simplicity). Due to the difficulties associated with temperature measurement, results at three bed depths (100, 300 and 500 mm down the bed) are averaged to obtain a single value for the bed.

3.1.1. Average Maximum Temperature

Figure 4 shows the comparison between measured and predicted average maximum temperatures for the 25 sinter pot tests. It is seen that the predicted and measured maximum bed temperatures agree well for the 25 cases, although predicted values are slightly higher than measured values. Both the predicted and measured average maximum temperatures range from 1200°C to 1400°C for the 25 cases. The sub-models of heat and mass transfer, as well as coke combustion and fluxes calcination reactions and the drying and condensation of water have a large influence on maximum bed temperature and Fig. 4 suggests these sub-models are reasonably well described in the model.

3.1.2. Residence Time > 1100°C

The comparison between the predicted and measured residence time for the 25 sinter pot tests is shown in Fig. 5. It is seen that overall the predicted results compare well with the measured results. This comparison indicates that the model can reasonably predict residence time at temperatures of greater than 1100°C.

---

Fig. 2. Comparison between typical measured and predicted temperature profiles at three bed depths.

Fig. 3. Three parameters derived from the sintering bed temperature profile: 1. maximum temperature, 2. residence time and 3. enclosed area.

Fig. 4. Comparison between measured and predicted average maximum temperature for the 25 sinter pot tests.
3.1.3. Enclosed Area $> 1100^\circ$C

The enclosed areas obtained from the predicted temperature profiles for the 25 sinter pot tests are compared with those obtained from the measured profiles in Fig. 6. It is seen that the predicted enclosed area values are slightly higher than the measured values. The enclosed area value is a function of the average maximum bed temperature and residence time and errors incurred in the determination of average maximum bed temperature and residence time will be carried over to the enclosed area results. However, given the very wide range of experimental conditions and the difficulties associated with temperature measurement, the agreement between the predicted and the measured results can be considered reasonable. Differences between predicted and measured enclosed areas could be partly due to heat loss around the pot wall, which is not taken into consideration in the model. This can result in a higher predicted temperature and enclosed area compared with the measured values. Omission of some exothermic and endothermic reactions, e.g., hematite decomposition and reduction at high temperatures can also change the enclosed area value slightly. In addition, the melting and solidification sub-model can also influence this value since it can change bed structure in the high temperature zone, the heat and mass transfer process and, consequently, bed temperature. Like most models reported in the literature, the present melting and solidification sub-model is based solely on thermodynamics while kinetics are not considered. Clearly, introducing the kinetics of melting and solidification into the model will influence the results.

3.2. Flame Front Speed

In iron ore sintering plants, flame front speed is an important variable determining productivity and sinter quality. In this study, flame front speed is obtained by dividing bed height by sintering time. Figure 7 compares predicted and measured flame front speeds for the 25 sinter pot tests. Good agreement is found in every case. As flame front speed is largely related to convection heat transfer, the agreement suggests that the heat and mass transfer sub-models are reasonable.

Studies of sinter pot test results show that denser ore mixes gave slower flame front speeds for the same post-ignition airflow rate. To investigate this, a set of 25 simulation cases were designed in which post-ignition airflow rate was increased from 80 to 200 $\text{m}^3/\text{h}$, while the bed bulk density increased from 1630 to 1830 $\text{kg/m}^3$. The predicted results are shown in Fig. 8. It is seen that flame front speed increas-
es with increasing post-ignition airflow rate and this relationship is almost linear under the chosen simulation conditions. For different bed bulk densities, the predicted result suggests faster flame front speeds at lower bed bulk density for the same post-ignition airflow rate. Lower bed bulk density means that the time to heat up the sinter mix from ambient temperature to coke combustion temperature will be shorter. Thus lower bed bulk density results in faster flame front speeds. These results are consistent with the experimental results. The obtained agreement further suggests that the heat and mass transfer sub-models are reasonable. As bed bulk density is related to the energy conservation of the solid phase, the agreement suggests that the energy conservation equation of the solid phase is reasonable.

3.3. Waste Gas Composition Profiles

A typical set of measured and the corresponding predicted waste gas compositions for O\(_2\), CO and CO\(_2\) are presented in Fig. 9(a). These results are from the same test as that used for temperature profile comparison shown in Fig. 2. Figure 9(a) shows good agreement between predicted and measured results.

Figure 9(a) shows that shortly after the completion of ignition (around 2 minutes), the volumetric concentrations of CO, O\(_2\) and CO\(_2\) in the waste gas remain relatively constant during most of the sintering period until at burn-through, and this can be termed the “steady-state waste gas composition” or “SSWGC”. Likewise, Fig. 9(b) shows that in the waste gas temperature profile there is a “steady-state waste gas temperature” (or “SSWGT”) during most of the sintering period. The SSWGC and SSWGT have been observed in both sinter pot tests and numerical simulations, and their values agree well with each other. The SSWGC of CO in volumetric percentage is around 2 vol.%. For O\(_2\) and CO\(_2\), the values are around 8 and 13 vol.%, respectively. The SSWGT value is around 55°C.

In Fig. 9(b), there is a large difference between the predicted and measured SSWGTs near burn-through. The most probable reason for this discrepancy is that experimental SSWGT is determined in the wind box, while the predicted values represent gas temperature at the bottom of the bed. Consequently, they are only comparable before burn-through but not towards the end of sintering. The reason for the existence of SSWGT has been explained in the earlier work. It is caused by the evaporation of water from near the flame front and condensation of this water in the lower bed because temperatures are below the dew point, and this results in the formation of the wet zone. The agreement with the experimental SSWGT indicates the reasonability of the drying and condensation sub-models.

Figure 10 compares the predicted and measured masses of CO and CO\(_2\) produced in the waste gas during the whole sintering period for the 25 test cases. Good agreement is found for both CO and CO\(_2\). It is observed that CO levels in the waste gas change much more than CO\(_2\) levels. The mass of CO in the waste gas ranges from 0.75–2.00 kg, while that for CO\(_2\) is 12.5–20.0 kg. These ranges reflect the differences in coke and fluxes levels used in the experimental tests. The good prediction of CO mass is an indication that the coke combustion sub-model is reasonable, since CO is essentially produced by the coke combustion reactions.
The good agreement of CO$_2$ mass indicates that the coke combustion as well as flux calcination sub-models are reasonable.

4. Sensitivity Analysis

One of the important aims in the development of this iron ore sintering model is to provide information on the ranking of the variables that influence sintering performance. Most of these cannot be obtained experimentally because the variables closely influence each other. For example, changing the mix moisture will impact granulation, bed voidage, bed bulk density and airflow rate. On the other hand, the model can change the mix moisture value in isolation while keeping all the other variables unchanged. This enables the separate influence of each variable on sintering performance to be qualified.

Sensitivity analyses were carried out in which the effects of nine input variables on sintering time and three temperature profile parameters were analyzed. The nine input variables are coke level (wt.%), limestone level (wt.%), moisture level (wt.%), post-ignition airflow rate (m$^3$ h$^{-1}$), bed voidage ($-$), bed bulk density (kg m$^{-3}$), solid thermal capacity (J kg$^{-1}$ K$^{-1}$), gas thermal capacity (J kg$^{-1}$ K$^{-1}$), and coke Sauter mean diameter SMD (mm), while the studied parameters are sintering time (min), maximum bed temperature ($^\circ$C), residence time (min) and enclosed area (min $^\circ$C).

The sensitivity coefficient $S$ of the studied parameter $P$ to the $i$-th input variable $IV$ is defined by the following formula:

$$S = \frac{P_i - P_0}{IV_i - IV_0}$$

where, $IV_0$ and $IV_i$ refer to the base case and non-base case values for the $i$-th input variable of interest; $P_i$ and $P_0$ are the corresponding values for the studied parameter. The sensitivity coefficient shows the relative change of the studied parameter with respect to the relative change of an input variable. The sensitivity analyses results for sintering time (min), maximum bed temperature ($^\circ$C), residence time (min) and enclosed area (min $^\circ$C) are shown in Figs. 11 to 14.

4.1. Sintering Time

Figure 11 shows that sintering time is most sensitive to the bulk density of the bed, and then the thermal capacities of solid and gas. The importance of bed bulk density on sintering time has been recognized in iron ore sintering practice. Green bed bulk density can significantly influence the sintering time and consequently the productivity. Solid thermal capacity is also important since it determines the time required to heat solid from the ambient temperature to coke combustion temperature. A larger solid thermal capacity means a longer time is required to reach coke combustion temperature and this in turn lengthens sintering time. The thermal capacity of the flowing gases also influences sintering time because a higher value will mean that more heat can be carried by the gases down the bed and this will result
in the region just ahead of the flame front reaching coke combustion temperatures sooner. A consequence of this is increased flame front speed. It may seem strange that Fig. 11 shows that post-ignition airflow rate does not have a high ranking. This is because the effect of varying post-ignition airflow rate is only small relative to the effects of changes of bed bulk density and solid and gas thermal capacities.

### 4.2. Maximum Bed Temperature

Figure 12 shows that the maximum bed temperature is very sensitive to coke levels, which is to be expected. Solid thermal capacity is again shown to influence the bed temperature greatly. However, thermal capacity of the gas is not as important as that of the solid. It is interesting that bed voidage has a relatively large influence on bed temperature and this is probably because of its influence on gas velocity and thence convective heat transfer, mass transfer and chemical reactions, etc.. Sensitivity analysis results also show that bed temperature is not very sensitive to post-ignition airflow rate. Predicted results show that bed temperature will decrease as airflow rate increases, however, the change in bed temperature is not large even when the airflow rate doubles in value.

### 4.3. Residence Time

Figure 13 shows the sensitivity of residence time to the nine input variables. As expected, results demonstrate the strong influence of coke level and coke diameter. In addition, the importance of bed bulk density and gas thermal capacity are also highlighted. Post-ignition airflow rate also greatly influences residence time. As airflow rate increases, the temperature profile will become narrower and consequently, residence time shortens.

### 4.4. Enclosed Area

In Fig. 14, the sensitivity of enclosed area at above 1100°C to the nine input variables is shown. Again the enclosed area is shown to be very sensitive to coke level since the enclosed area is dependent on the maximum bed temperature and residence time. Besides, it is noted that the predicted results highlight the importance of coke diameter on the enclosed area. The importance of coke diameter on iron ore sintering has been experimentally investigated by Loo.53 This work showed that the use of appropriate coke size distributions would increase the efficiency of the coke combustion process, resulting in lower levels of carbon monoxide in the waste gases and, consequently, higher sintering temperatures and higher productivity. This is justified since coke diameter to a large extent determines the coke combustion rate. If coke diameter is too large, combustion rate will be very slow thus generating less heat and the flame may be extinguished. On the other hand, if coke diameter is too small combustion rate will be very fast, the particle will be burnt up very quickly resulting in a narrower flame front and poor combustion efficiency. Heat generation may not be sufficient to sustain temperatures required for coke combustion and if this is the case the flame will be extinguished. This is also detrimental. Therefore, coke diameter has a large influence on bed temperature, the enclosed area and the residence time as well.

In the sensitivity analyses, bed bulk density, solid and gas thermal capacities, coke level and diameter and post-ignition airflow rate have been shown to significantly influence the sintering time and three temperature profile parameters. The influences of limestone and moisture levels are relatively minor in comparison.

### 5. Discussion

Table 1 provides a summary of eleven iron ore sintering models reported in the literature and the ZJU-BHP Billiton model. Of the eleven, nine are one-dimensional models. The table also provides succinct comparison between the models. For drying and condensation, a two-step stage is widely assumed. For coke combustion, a two-step reaction involving CO formation and its subsequent oxidation is used. As coke particles do not exist as free particles, the ZJU-BHP Billiton coke combustion models also includes a mass transfer resistance term to take into consideration the presence of materials, e.g., iron ore, limestone and dolomite, encapsulating them. For momentum equation, a more comprehensive equation is adopted by the ZJU-BHP Billiton model, in which the accumulation term is considered and a variable flow resistance is assumed in different zones. All heat transfer modes, viz., convection, solid conduction and solid radiation are also taken into account in the ZJU-BHP Billiton model.

In the last column of Table 1, summaries are given on work carried out to test predicted model results with experimental pot test results. It is clear that significantly much more studies have been carried out to test the validity of the ZJU-BHP Billiton model. In the area of temperature profile prediction this paper has not just considered how well predicted and measured profiles match – in position (on the temperature-time graph) and shape. Quantitative comparisons were also carried out in the areas of maximum sintering temperatures, residence time and enclosed area – hitherto never been done. Sensitivity studies were also carried out to rank the factors influencing sintering time and the important temperature profile parameters. In summary, the comparative study of predicted and experimental results reported in this paper is the most comprehensive.

It is critically important to note that experimental pot test results – particularly in the area of bed temperatures - are not ‘fully correct and true’. The reasons are discussed at length by Loo et al.15 Although the work is carried using superior procedures and with the greatest care there are inherent difficulties in measuring bed temperatures. This means that experimental results obtained by Loo et al.15 and used in this paper are good average values for a large number of tests. However, because they do not represent ‘true’ (if there is such a thing) bed temperatures, it is unreasonable to conclude that the model is inferior when there is an imperfect match with experimental temperatures. The experimental results used are, nonetheless, the best available for this study.

A method to assess the capability of the ZJU-BHP Billiton model14 against models reported in the literature is to use other input data. With the exception of Yang et al.89 most of the papers listed in Table 1 do not provide much experimental data. Using the cited data of Yang et al.89 as inputs into the ZJU-BHP Billiton model a second set of predicted predictions were performed.
The results of Yang et al. show the measured and predicted waste gas compositions. Nonetheless, the two figures suggest that the ZJU-BHP Billiton model can give results that better match the measured maximum bed temperature, steady-state CO₂ and CO compositions results. This good comparison also suggests that the ZJU-BHP Billiton model can also predict sintering in the pot used by Yang et al. in the area of sensitivity studies, one comparison can be made with the predictions of other studies. Sensitivity analyses given in Fig. 11 shows that mix moisture level has a relatively minor importance on sintering time compared

Table 1. Performance comparisons between the ZJU-BHP Billiton model and other existing numerical models of iron ore sintering.

<table>
<thead>
<tr>
<th>Researchers</th>
<th>Model Type</th>
<th>Drying &amp; Condensation</th>
<th>Melting &amp; Solidification</th>
<th>Coke Combustion</th>
<th>Momentum Equation</th>
<th>Heat Transfer Modes</th>
<th>Heat &amp; Mass Transfer Correlations</th>
<th>Comparison of model and experimental results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young et al.</td>
<td>1-D transient</td>
<td>Two-step drying process</td>
<td>Not included explicitly in energy equation, but considered by modifying the specific heat of solid in the presence of melt</td>
<td>One-step reaction: ( C + \frac{1}{2}O_2 \rightarrow CO )</td>
<td>Shrinking-core model</td>
<td>Convection only</td>
<td>Ranz-Marshall’s correlation for heat and mass transfer</td>
<td>None</td>
</tr>
<tr>
<td>Yoshinaga et al.</td>
<td>1-D transient</td>
<td>Three-step drying process</td>
<td>Temperature dependent thermodynamic melting and solidification model</td>
<td>One-step reaction: ( C + O_2 \rightarrow CO )</td>
<td>Shrinking-core model</td>
<td>Convection only</td>
<td>Unknown</td>
<td>One comparison of gas composition, none on temperature profile or flame front speed, no sensitivity analysis</td>
</tr>
<tr>
<td>Toda et al.</td>
<td>1-D transient</td>
<td>Two-step drying process</td>
<td>A semi-empirical kinetic melting model considering the effects of melting heat, ore density, ore specific heat, ore conductivity</td>
<td>Two-step reaction: ( C + \frac{1}{2}O_2 \rightarrow CO )</td>
<td>Shrinking-core model</td>
<td>Convection and solid conduction</td>
<td>Ranz-Marshall’s correlation for heat and mass transfer</td>
<td>None</td>
</tr>
<tr>
<td>Cumming et al.</td>
<td>1-D transient</td>
<td>Semi-empirical correlations</td>
<td>Temperature and composition dependent thermodynamic melting and solidification model</td>
<td>Ergun equation</td>
<td>Convection only</td>
<td>Kuni-Suzuki’s correlation for heat and mass transfer</td>
<td>One comparison on temperature profile, none on gas composition or flame front speed, no sensitivity analysis</td>
<td></td>
</tr>
<tr>
<td>Paterson et al.</td>
<td>1-D transient</td>
<td>Two-step drying process</td>
<td>Temperature and composition dependent thermodynamic melting and solidification model in combination with phase diagram</td>
<td>Ergun equation</td>
<td>Convection only</td>
<td>Experimentally determined heat transfer coefficient for the sintered zone</td>
<td>Eight comparisons on temperature profile, none on gas composition, flame front speed, no sensitivity analysis</td>
<td></td>
</tr>
<tr>
<td>Venkataramana et al.</td>
<td>1-D transient</td>
<td>Unknown</td>
<td>Paterson’s model</td>
<td>Ergun equation</td>
<td>Convection only</td>
<td>Kuni-Suzuki’s correlation for heat and mass transfer</td>
<td>Three comparisons on temperature profile, none on gas composition or flame front speed, no sensitivity analysis</td>
<td></td>
</tr>
<tr>
<td>Ramos et al.</td>
<td>1-D transient</td>
<td>Two-step drying process</td>
<td>Temperature and composition dependent thermodynamic melting and solidification model in combination with phase diagram</td>
<td>One-step reaction: ( C + O_2 \rightarrow CO )</td>
<td>Shrinking-core model</td>
<td>Convection only</td>
<td>Ranz-Marshall’s correlation for heat and mass transfer</td>
<td>None</td>
</tr>
<tr>
<td>Mittlerlehner et al.</td>
<td>1-D transient</td>
<td>One-step drying process</td>
<td>Temperature and composition dependent thermodynamic melting and solidification model in combination with phase diagram</td>
<td>Two-step reaction: ( C + O_2 \rightarrow CO )</td>
<td>Modified Ergun equation</td>
<td>Convection and solid conduction</td>
<td>Gnielinski’s correlation for heat and mass transfer</td>
<td>One comparison of gas composition, one comparison of flame front speed, none on temperature profile, sensitivity analysis on two important parameters</td>
</tr>
<tr>
<td>Yang et al.</td>
<td>1-D transient</td>
<td>One-step drying process</td>
<td>Not included</td>
<td>Two-step reaction: ( C + \frac{1}{2}O_2 \rightarrow CO )</td>
<td>Shrinking-core model</td>
<td>Convection, solid conduction and solid radiation</td>
<td>Wakao-Kaganei’s correlation for heat and mass transfer</td>
<td>One comparison of gas composition, one comparison of temperature profile, four comparisons of flame front speed, no sensitivity analysis</td>
</tr>
<tr>
<td>Nait et al.</td>
<td>2-D transient</td>
<td>One-step drying process</td>
<td>Temperature and composition dependent thermodynamic melting and solidification model</td>
<td>One-step reaction: ( C + O_2 \rightarrow CO )</td>
<td>Shrinking-core model</td>
<td>Ergun equation</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
<tr>
<td>Yamakawa et al.</td>
<td>3-D transient</td>
<td>One-step drying process</td>
<td>Temperature and composition dependent thermodynamic melting and solidification model in combination with phase diagram</td>
<td>Complete momentum equation with source term calculated from modified Ergun equation</td>
<td>Convection and solid conduction</td>
<td>Ranz-Marshall’s correlation for heat and mass transfer</td>
<td>One comparison of gas composition, one comparison of temperature profile, none on flame front speed, no sensitivity analysis</td>
<td></td>
</tr>
</tbody>
</table>

Note: in the table, “Unknown” means the specific part is not explicitly described in the paper, thus the model details are unknown.
with coke level. Mitterlehner et al.\textsuperscript{24) came to this same conclusion in their work.

6. Conclusions

To determine the predictive capability and robustness of the ZJU-BHP Billiton iron ore sintering model, results from twenty-five sinter pot tests covering a wider range of operating conditions, are used in this study. Detailed quantitative predicted versus measured comparisons were carried out in the areas of bed temperature profile (average maximum temperature, residence time and enclosed area), flame front speed (sintering time) and gas composition. Additionally, quantitative comparisons were also made between the ZJU-BHP Billiton model and models reported in the literature. The acceptable comparisons obtained indicate that the sub-models used to describe significant physico-chemical phenomena in the iron ore sintering process are reasonable.

In particular, the results of this study indicate that the important sub-models such as, coke combustion, fluxes calcination, drying and condensation of water as well as heat and mass transfer describe the respective processes well. Comparisons were not as good for some parameters indicating that improvements could be made. For example, the melting and solidification sub-model can be improved to include kinetic factors. The difference between predicted and measured enclosed area in the temperature profiles can be attributed to the omission of heat loss and some endothermic or exothermic reactions e.g., hematite decomposition and reduction in the model, as well as the difficulties associated with bed temperature measurement. In some of these areas improvements can be made to the model.

The steady-state waste gas composition (SSWGC) and steady-state waste gas temperature (SSWGT) observed in sinter pot tests compare well with equivalent results obtained from the numerical simulations. The influences of ore density and post-ignition airflow rate on the flame front speed are analyzed using the model results. Sensitivity analyses show that bed bulk density, solid and gas thermal capacities, coke level and diameter and post-ignition airflow rate have large influences on sintering time and the 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 for Prof. Zhou by the Key Technologies R&D Program of China (2011BAA04B01) is also gratefully acknowledged.

REFERENCES

1) S. Zhang: 6th European Coke and Ironmaking Cong. (ECIC), Session 1, Steel Institute VDEh, Düsseldorf, (2011), CD-ROM.
5) C. E. Loo: ISIJ Int., 52 (2012), 1550.
16) C. E. Loo, N. Tame and C. P. Benny: ISIJ Int., 52 (2012), 967.

© 2012 ISIJ