

Mathematical Model to Estimate the Rate Parameters and Thermal Efficiency for the Reduction of Iron Ore–Coal Composite Pellets in Multi-layer Bed at Rotary Hearth Furnace

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Abstract Reduction of iron ore–coal composite pellets at a rotary hearth furnace (RHF) could be an energy efficient process under optimized design and operating conditions. The present study aims to analyze such process through process models for optimization of thermal efficiency. In the present article, a mathematical model has been described to calculate the rate parameters, evolution of various phases, temperature profile, and thermal efficiency of the process. Experiments have been carried out for reduction of iron ore–coal composite pellets in multi-layers at laboratory scale RHF. It has been observed that while the total average time of reduction for three layer bed at 1,200 °C is 48 min, the average time of reduction at 1,300 °C is estimated as 11 min only. The thermal efficiency of the process is found to be maximum for three layer bed and least for the single layer bed. Extra fuel in terms of carbon equivalent has also been reported.

Keywords Rotary hearth furnace · Reduction kinetics · Mathematical model · Iron ore–coal composite pellets · Thermal efficiency

1 Introduction

Blast furnace iron making is the most efficient and important iron making process till today. However, inspite of several recent advancements through blast additives and tuyser injections, blast furnace requires a minimum amount of coke, quality ferrous burden, and produces

approximately 1 tonne of CO₂/tones of hot metal [1, 2]. Besides huge amount of iron ore fines and coal fines are generated during mining and in washeries, out of which a large fraction of fines remains unused till today.

Rotary hearth furnace (RHF) closely simulates the dry zone in a blast furnace where a moving hearth in a circular path carries the burden material through a sequence of different temperature regimes starting from preheating to reduction to cooling zone. The major differences from blast furnace is that in RHF the bed is stationary and gas flows over the bed, which allows one to compromise with inferior burden material like iron ore–coal composite pellets made from otherwise unusable non coking coal fines and iron ore dust. Although some successful commercial processes have evolved based on composite pellets reduction at RHF like FASTMELT, ITmk3 [3, 4], there appears to be plenty of scope to investigate in this direction, especially to analyze these processes through process models for optimization of thermal efficiency. The major drawback of RHF lies in heat transfer limitation in a multi-layer bed. Since the coal based direct reduction is highly endothermic and heat is supplied from hot gas over the bed at RHF, beyond a certain metallization the reduction in multilayer bed becomes ineffective [5]. In that case attaching a post processing unit for smelting of partially reduced pellets from RHF could be a new process. However, research should continue to improve the extent of reduction in RHF for making such process techno–economically viable. It would be an interesting study to look for the design and operating parameters that can enhance the heat and mass conductance of the pellet bed in RHF. Subsequently, development of a mathematical model to understand the phase evolution and heat transfer in the multi-layer bed would be essential.

Reduction of composite pellets is non-isothermal in nature. Several previous investigators however developed

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simpler isothermal models of composite pellets where the first order isothermal models were found to be representative of experimental data only in certain range of time and temperatures. Later on some non-isothermal models for iron ore-carbon mixture/pellets were also developed [6, 7]. A good review of all this work have been done by Donskoi et al. [8]. Most recently, Chaudhury et al. [9] reported a semi-empirical model for packed bed reduction of composite pellets in a side heated reactor, where they estimated the rate parameters from experimental data by employing an evolutionary optimization tool, genetic algorithm (GA). Such models coupled with heat transfer equation could be useful for calculating phase evaluation, and thermal efficiency of the reactor. In the present study a similar methodology has been adopted to understand the reduction kinetics and thermal efficiency in RHF. The aims of the present investigation have been to estimate the rate parameters for reduction of iron ore coal composite pellets in multi-layer bed in RHF and subsequently to calculate the total time of reduction, sensible and chemical heat absorbed, thermal efficiency of the process even beyond the experimental range.

2 The Models

In the present study, two mathematical formulations are developed. The first is the kinetic model, which is used to estimate the reaction rate constants, and evolution of various phases of iron oxide and metallic iron during the course of reduction. The other is the energy balance model of a multi layer bed in RHF to determine the transient evolution of temperature profile along vertical distance and subsequently to determine the total heat absorbed for partial/complete reduction and thermal efficiency of the process. The thermal model uses the phase evolution data from kinetic model for calculation of heat effect of reaction. The limitation of the model lies in the fact that the model is semi-empirical in nature and has to be applied for different specific design conditions of the bed for estimating the rate parameters.

2.1 Kinetic Model

It is accepted that reduction of iron ore in an iron ore-carbon composite pellet proceeds by the intermediate oxides formation, which include conversion from hematite to magnetite, magnetite to wustite and finally wustite to iron (reactions 1 to 3) and reduction takes place by gaseous intermediates mainly through the regeneration of CO by carbon gasification reaction (reaction 4).



Assuming the rate of transformation in each step is of the first order, the mass balance equations for transformation at each step is given by Eqs. (5) to (8).

$$\frac{dC_H}{dt} = -C_H A_H \exp\left(-\frac{E_H}{RT}\right) \quad (5)$$

$$\frac{dC_M}{dt} = x C_H A_H \exp\left(-\frac{E_H}{RT}\right) - C_M A_M \exp\left(-\frac{E_M}{RT}\right) \quad (6)$$

$$\frac{dC_W}{dt} = y C_M A_M \exp\left(-\frac{E_M}{RT}\right) - C_W A_W \exp\left(-\frac{E_W}{RT}\right) \quad (7)$$

$$\frac{dC_F}{dt} = z C_W A_W \exp\left(-\frac{E_W}{RT}\right) \quad (8)$$

The rate of carbon removal can be calculated by knowing the evolution of iron oxide phases as follows:

$$\frac{dC}{dt} = 0.025 \left(\frac{dC_H}{dt}\right) + 0.0517 \left(\frac{dC_M}{dt}\right) + 0.167 \left(\frac{dC_W}{dt}\right) \quad (9)$$

The above equations represent four first order ordinary differential equations with six unknown rate parameters (A_H , A_M , A_W , E_H , E_M , E_W) and four primary unknowns like concentrations (kg/m^3 of the bed) of hematite (C_H), magnetite (C_M), wustite (C_W) and iron (C_F). A_H , A_M , A_W (pre exponential factors) and E_H , E_M , E_W (activation energy values) represent the rate parameters for hematite, magnetite and wustite transformations, respectively. R is the universal gas constant while T is the reduction temperature in Kelvin. Since there are six extra variables than the number of equations, these variables—the rate parameters are required to be estimated first to get unique solution from four equations. In the present work those parameters are estimated by applying an optimization procedure, the GA. Thereafter, the evolution of phases is predicted based on these optimized rate parameters. In the present study, experiments are carried out with three layers of composite pellets in RHF. Since three layers will be subjected to different heat fluxes from the top, rate parameters are estimated separately for three layers. Also the diameters of the pellet size were considered in two levels, i.e. at 10 and 16 mm. Consequently, the kinetic model was run separately for two different pellet sizes and three different layers (total $3 \times 2 = 6$ cases); because the estimated apparent rate parameters are supposed to be influenced by heat and mass transfer which are in turn

supposed to be influenced by the number of pellet layers and pellet sizes.

It may be noted that reactions 1–3, apparently represent the reduction of various iron oxides by CO only. Actually some reduction also takes place by hydrogen of volatile. Therefore, the estimated rate parameters for reactions 1–3, would represent the combined effect of reduction by CO as well as by H₂. Also the carbon rate given by Eq. 9, actually represents the rate of consumption of carbon equivalent to the combined reduction by CO and H₂ of volatile. From this point of view, the carbon calculated will be more than actual carbon consumed.

2.2 Methodology for Estimation of Rate Parameters

GA randomly generates an initial population of individuals each of which represents a set of unknown rate parameters to be estimated. Then GA sends each individual to kinetic model which evaluates the quality of individual by comparing the predicted solid phases with the experimentally determined phases obtained through quantitative XRD analysis of reduced pellets. In kinetic model we solve the set of four ordinary differential equations by 4th order RK using the rate parameters provided by the GA individual. The quality of the individual is judged by fitness parameter which is defined as

$$FP = \frac{1}{\sqrt{[(H_p - H_e)^2 + (M_p - M_e)^2 + (W_p - W_e)^2 + (F_p - F_e)^2]}} \tag{9}$$

where, *H*, *M*, *W*, *F* represent the fraction of hematite, magnetite, wustite and iron in the reduced pellet. The subscripts p and e represent the predicted and experimental values, respectively. Here higher is the fitness parameter, minimum is the difference between the predicted and experimental value of the fractional phases, and better is the individual. The kinetic model sends back the information regarding the quality of the individual through fitness parameter to the GA routine. After evaluating all the individuals of the current population by kinetic model, GA generates a better population for the next generation. The population for the next generation is created through some biological operators like tournament selection, crossover, mutation etc., based on the general principle of genetics. Thereafter, GA evaluates its individual of the next generation through kinetic model and the process repeats till the average fitness of two consecutive generations do not change any more. Schematically, the process may be described as in Fig. 1. The best individual with maximum fitness is then selected from final generation as the optimum individual. The best individual contains the optimum rate parameters for the conversion of hematite to

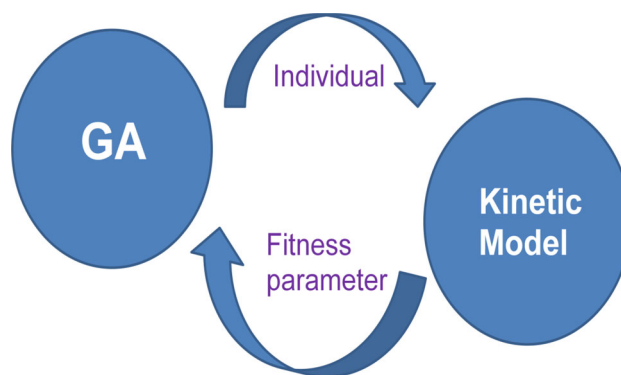


Fig. 1 The schematics of interaction between GA and the kinetic model (online version in colour)

magnetite, magnetite to wustite, and wustite to metallic iron. Using these optimum rate parameters, the evaluation of hematite, magnetite, wustite and iron can be obtained for a particular set of operating parameters for which the experiments have been carried out. A GA routine developed by Kalyanmoy Deb is used here [10].

2.3 Thermal Model

A transient one dimensional heat conduction model has been used to calculate the temporal evolution of temperature profile across the vertical direction of the multilayer bed. The model considers the heat effects of reactions which has been calculated based on the temporal evolution of various phases during reduction, as calculated by the kinetic model. The model also considers thermal properties as weighted average of various phases based on their local concentration, and local temperature at a particular time. The pellet bed has been considered as solid. The effect of bed porosity, local melting and consolidation has been taken care of by introducing a factor to the effective conductivity. The governing equation of heat balance equation may be given as:

$$\frac{\partial}{\partial t} (\rho C_p T) = \frac{\partial}{\partial Z} \left(K_{eff} \frac{\partial T}{\partial Z} \right) + \sum \Delta H_i R_i \tag{10}$$

where *T* is the temperature in Kelvin, ρ and *C_p* are the temperature dependent density and specific heat, *t* is time, *K_{eff}* is the effective thermal conductivity of the pellet. The term $\sum \Delta H_i R_i$ represents the heat effects of reactions. The terms ΔH_i and *R_i* are heat of reaction and rate of reaction for the *i*th compound, respectively. The temporal evolutions of rates for various phases are taken from the kinetic model. The temperature dependent thermal conductivity, heat of reaction and specific heat are function of temperature and taken from literature [11].

Boundary conditions (*t* > 0) may be given as:

For top surface of the pellet bed: The top surface is assumed to be at the furnace temperature assuming

Table 1 Chemical analysis of raw material used in the present study

Raw material	Fe ₂ O ₃ (%)	SiO ₂ (%)	Fe (%)	CaO (%)	MgO (%)	P ₂ O ₅ (%)	Al ₂ O ₃ (%)	FC (%)	VM	ASH
Iron ore	86.8	5.89	–	0.103	0.047	0.059	6.89	–	–	–
Coal	–	7.41		0.8	0.18	1.025	3.21	60.9	25.4	13.7

**Fig. 2** RHF at IIT Kharagpur used for the present study (online version in colour)

negligible resistance in the thermal boundary layer between the furnace atmosphere and the top surface.

$$T = 1273 \text{ K} \quad (\text{For Preheating Zone, up to } t = 10\text{min})$$

$$T = 1473 \text{ K} \quad (\text{For Reduction Zone, beyond 10min})$$

For Bottom surface of the pellet bed: A no heat flux condition is assumed:

$$-K \frac{\partial T}{\partial t} = 0 \quad (11)$$

2.4 Experimental

The chemical composition of the iron ore and coal fines used in the investigation is given in Table 1. Iron-ore fines, and coal fines (less than 150 μm), and a small amount of bentonite (1 wt%) as binder are mixed thoroughly in a rotating glass bottle for 5 h. The molar ratio of hematite to carbon in the pellet is maintained at 1:2.88. After dry mixing water is added and pelletized by hand rolling of two different sizes 10 mm and 16 mm. Green pellets are cured in the oven at 200 $^{\circ}\text{C}$ for 2 h before they become ready for reduction experiments. After curing, the pellets are reduced in a RHF installed at the Steel Technology Centre, IIT Kharagpur, India (Fig. 2). The furnace has an outer diameter of 1.93 m, inner diameter of 1.25 m, height 0.5 m and a water cooled hearth. There are 6 different temperature zones distributed along the circumference of the furnace and temperatures are preset for each zone as required by the design of the experiment. The first three zones serve as preheating zone; the fourth zone is set to the highest temperature required for reduction while the last two zones

serve as the cooling zone. Heating is done from the top by radiation from Kanthal heating elements and the temperature is measured by two thermocouples in each zone (one at the centre and one at the periphery). A variable frequency drive (VFD) attached to the furnace allows a variation in time of complete hearth revolution from 28 to 56 min. A constant nitrogen flow of 5 litres/min is provided in each zone to maintain an inert atmosphere for reduction. Crucibles containing three layers of pellets of two different sizes of pellets namely 10 and 16 mm are entered sequentially into zone 1 of the furnace at a time interval of 3 min. Actual reduction of pellets is carried out for 10 min at 1,200 $^{\circ}\text{C}$ in the reduction zone of the furnace although the total residence time of the sample in the furnace is kept at 56 min including preheating and cooling of pellets. After the reduction is over, the pellets are cooled in the furnace under nitrogen. The weight of reduced pellets along with the crucible is noted after reduction. The reduced pellets are analyzed for remaining carbon % by dry combustion method using a Strohlein's apparatus. Oxygen removed is calculated as weight loss of the bed—carbon loss. Carbon loss is calculated as initial total carbon minus residual carbon in the reduced pellet. Total initial carbon is calculated as: $100 - \% \text{ash} - 0.47 * \text{VM}$ [12].

3 Results and Discussion

3.1 Results from Experiments

Table 2 depicts the data for oxygen mass balance and degree of reduction at various depths of the pellet bed for two different sizes of pellets. In case of multi-layer pellet bed containing pellets of 10 mm size, it is observed top layer shows higher reduction percentage (49 %) than that of middle layer (34 %) and bottom layer (18 %). It is also observed that as the size of pellet increases the extent of reduction decreases for all layers.

Figure 3 show the XRD pattern of reduced iron ore–coal composite pellets at 1,200 $^{\circ}\text{C}$ for 10 min for top, middle and bottom layers. An attempt has also been made to quantify the relative abundance of various phases by using Rietveld quantitative XRD analysis that is based on estimating relative intensities of the identified phases in XRD pattern and subsequent statistical analysis. An estimation of the relative abundance of reduced iron oxides, iron and

Table 2 Degree of reduction values at different layers in pellet bed of iron ore–coal composite pellets at RHF at 1,200 °C

Size	Layer	Initial wt. (g)	Final wt. (g)	Initial oxygen (g)	Initial total carbon ^a (g)	Final carbon (g)	Oxygen loss (g)	Degree of reduction (%)
10 mm	TL	24.33	18.25	5.0 ^b	3.61	0.05	2.52	50
	ML	20.78	16.4	4.27	3.09	0.09	1.38	32
	BL	20.09	16.47	4.13	2.99	0.12	0.75	18
16 mm	TL	20.78	16.2	4.27	3.09	0.06	1.50	35
	ML	20.34	16.2	4.18	3.03	0.09	1.20	29
	BL	20.22	16.82	4.16	3.00	0.10	0.50	12

^a % total carbon = 100 – %ash-0.47 × %VM [12]

^b % coal in the initial charge are 20 wt% and % iron ore is 79 wt% (rest 1 % is bentonite)

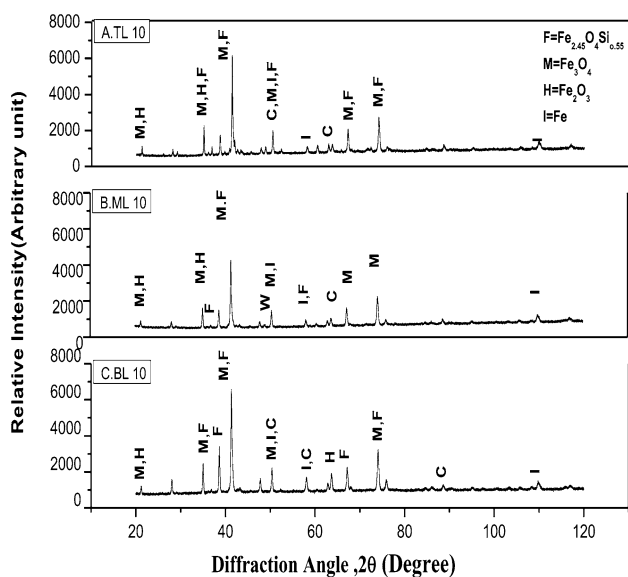


Fig. 3 XRD pattern for reduced pellets of 10 mm diameter: **a** top layer (TL 10), **b** middle layer (ML 10), **c** bottom layer (BL 10)

fayalite in reduced pellets is delineated with the help of pie charts displayed in Fig. 4.

It is to be noted that the gangue in the initial mass is 13 % and so in the reduced mass after volatile and partial oxygen and carbon removal, its percentage will further increase. But Rietveld analysis overpredicts combined amount of metallic iron and its oxides to around 91 %. Because, in XRD we missed peaks whose weight percentages are small like CaO, MgO, P₂O₅ and even Al₂O₃ which is slightly more than 5 % in the pellet. We got silica peaks possibly because it appears in the form of fayalite which is more than 10 % in the reduced mass and detected by XRD. Therefore, the combined percentages of iron oxides and metallic iron are overestimated based on reduced mass excluding the gangue constituents except SiO₂. We acknowledge this inaccuracy. Table 3 shows the

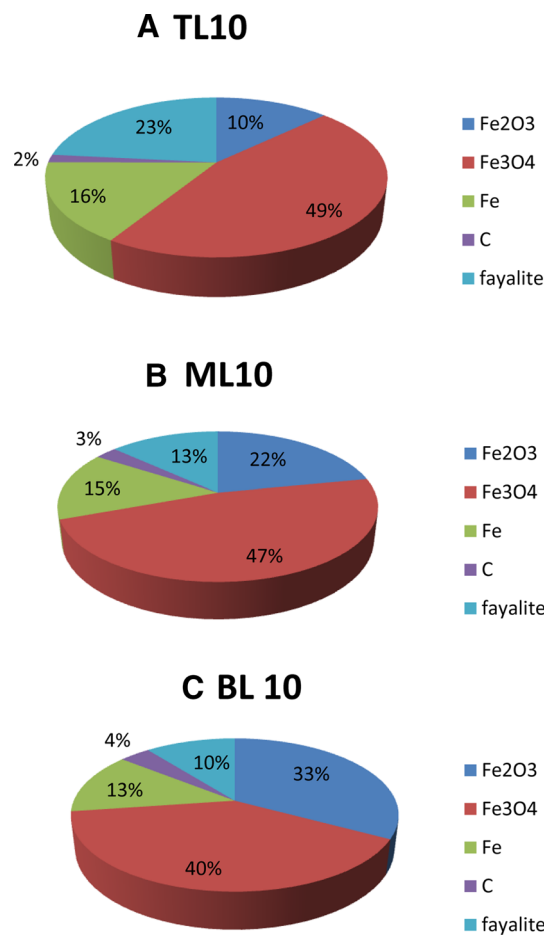


Fig. 4 Relative abundance of various iron oxide phases, metallic iron and fayalite calculated based on XRD pattern of **a** top layer, **b** middle layer, **c** bottom layer ore–coal composite pallets of diameter 10 mm (online version in colour)

discrepancy between mass balance and the XRD quantification for the top layer (TL).

The experimental phase evolution thus calculated is used in the kinetic model to calculate the fitness parameter and subsequently rate parameters.

Table 3 Discrepancy between quantitative XRD analysis and mass balance for the top layer of 10 mm pellet bed

	Total mass	Ore (g)	Coal (g)	SiO ₂	Al ₂ O ₃	Others (CaO + MgO + P ₂ O ₅)	Total gangue	% Total carbon (including VM)	% Gangue	% Iron and its oxides
Initial mass	24.33	19.2	4.86	1.49	1.48	0.14	3.11	15	13	72
Reduced mass	18.25	2		1.49	1.48	0.14	3.11 1.5 ^a	0.27 0.27	17.2 8.2 ^a	81.36 91 ^a

^a With considering gangue constituents except SiO₂

Table 4 Estimated rate parameters for evolution of various oxide phases during reduction of iron ore–coal composite pellets at 1,200 °C for 10 min

Size of the pellet (mm)	Estimated rate Parameters	$A_H \times 10^{-17}(\text{s}^{-1})$	$A_m \times 10^{-16}(\text{s}^{-1})$	$A_w \times 10^{-13}(\text{s}^{-1})$	E_H (kJ/mol)	E_m (kJ/mol)	E_w (kJ/mol)
10	TL	74.04	81.31	76.92	585.4	550.05	400.48
	ML	67.36	71.19	65.76	600.7	580.85	421.6
	BL	54.3	60.7	53.43	604.015	583.4	431.3
16	TL	60.034	63.76	51.72	589.401	562.099	419.926
	ML	79.71	92.28868	68.299	608.166	582.489	429.715
	BL	90.6487	95.6686	86.20	611.77	590.530	450.141

Table 5 Comparison between predicted and experimentally obtained oxide phases of the representative pellets from different layers reduced at 1,200 °C for 10 min

Layers	Phase (wt%)	Predicted by model	Measured from XRD chart
Top layer	Fe ₂ O ₃	11.7	10.768
	Fe ₃ O ₄	48.864	49.0
	FeO	17.42	16.235
	Fe	17.31	16.0
Middle layer	Fe ₂ O ₃	22.92061	23
	Fe ₃ O ₄	46.91836	47
	FeO	10.3892	9.1
	Fe	16.06447	15
Bottom layer	Fe ₂ O ₃	34.75024	33.0
	Fe ₃ O ₄	41.72637	40.0
	FeO	8.791108	7.0588
	Fe	14.73228	13

3.2 Results from Kinetic Model

The estimated rate parameters for all three layers for two different sizes of pellets are presented in Table 4. Table 5 depicts the comparison of phases estimated through XRD analysis and model prediction, where a good agreement could be observed. The predicted phase evolution with time for top layer pellets of diameter 10 mm at 1,200 °C is displayed in the Fig. 5. Figure 6 shows the extrapolated phase evaluation plot beyond experimental reduction time (600 s) corresponding to Fig. 4. It has been calculated based on estimated rate parameters using experimental data up to 600 s, which assumes that the reaction mechanism does not alter in the time period beyond 600 s. It is clear that up to 10 min the reduction is partial as indicated by the

presence of all oxide phases namely, hematite, magnetite, wustite; while at 3,000 s the extrapolated oxide phases and carbon (added stoichiometric to hematite) diminishes to zero and all hematite is converted to metallic iron. Calculation started with initial hematite concentration of 1,428 kg/m³ (8.9 kg mol/m³) which finally converted to 17.8 kg mol of iron/m³, or 1,000 kg/m³. This confirms the iron mass balance. Similar extrapolated phase evolutions for other two layers are also observed but only differing in magnitudes.

3.3 Results of Thermal Model

Temperature variation against time at various positions from top surface of the 30 mm pellet bed (three layer pellet

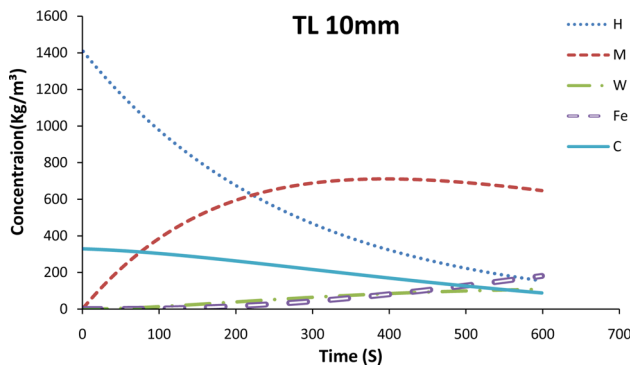


Fig. 5 Predicted concentrations of various oxide phases, as well pure iron, and carbon as a function of time during reduction at 1,200 °C for top layer of pellet bed with 10 mm pellet size (online version in colour)

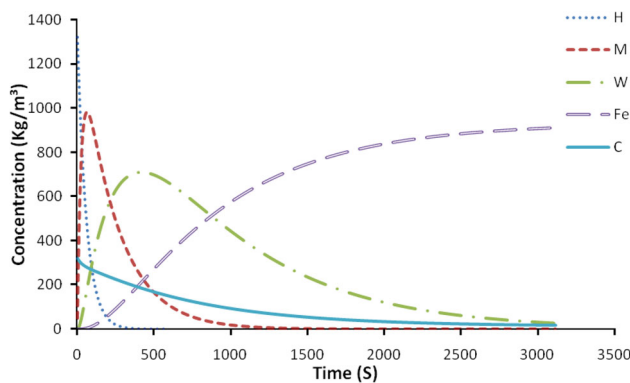


Fig. 6 Extrapolated phase evolution beyond reduction time based on estimated rate parameters at 1,200 °C for top layer of pellet bed with 10 mm pellet size (online version in colour)

bed with pellet size of 10 mm) based on extrapolated phase evolution for reduction zone temperature at 1,200 °C is depicted in Fig. 7. It may be mentioned here that the temperature change at various locations are the manifestation of sensible heat gain and the overall endothermic heat of reaction. Therefore a rise in temperature indicates that sensible heat gain is greater than the heat loss by endothermic heat of reaction and vice versa. A stationary temperature indicates the sensible heat gain is equal to endothermic reaction heat loss. It is observed that initially up to 500 s temperature at upper layers increases to saturation temperature of top layer and then start decreasing while bottom layer starts getting heated up and slowly increases to above 800 °C after 1,200 s. But the layer just below the top most layer do not show any indication of temperature fall; rather it increases further to the reduction zone temperature by 1,200 s, indicating reaction heat loss is negligible compared to sensible heat gain from top. But after 1,200 s, both the temperatures at all layers starts falling fast for next 5 min indicating dominating heat loss by endothermic reaction compared to sensible heat gain.

Thereafter, temperature at all layers starts increasing but at much slower pace indicating continuation of reaction up to 3,000 s.

3.4 Thermal Efficiency

Based on experimental reduction of three layer composite pellets for 10 min at 1,200 °C, predictions have also been made for 100 % reduction at 1,200 °C as well as for 1,300 °C, assuming the average rate parameters for three layers remains unaltered beyond experimental range. It has been observed that while the total average time of reduction for three layer bed at 1,200 °C is 48 min, the average time of reduction at 1,300 °C is only 11 min. Incidentally, it is found that ITmk3 process also takes around 10 min for complete reduction [3]. It may be noted that ITmk3 process also involve solid state reduction leading to separation of metalized pellet (nugget) and the slag. Therefore, although it may not be considered as direct validation, this lends some confidence in our model.

Calculations have also been made to estimate the sensible and the chemical heat absorbed for 100 % reduction at 1,200 °C through model predictions beyond the experimental conditions for all three layers separately and depicted in Table 6. The thermal efficiency of the process, defined as the ratio of minimum theoretical heat to the total heat absorbed (reaction heat + sensible heat), have been calculated for all three layers. Theoretical heat has been calculated from enthalpy data for the overall direct reduction of hematite to iron, given as reaction (12):



From Table 6, it is observed that the thermal efficiency of the three layers is significantly higher (66 %) than the two layers (56 %), or single layer (54 %). This due to the fact that sensible heat absorbed by the three layers per mole of Fe₂O₃ (218 kJ) is much lower than those consumed by two layers (340 kJ) or single layer (379 kJ). The above results indicate that thermal efficiency increases with increase in number of layers up to three layers. But what happens beyond three layers is required to be seen through future experiments with more number of layers. Calculations have also been made to estimate the extra fuel to be burned in excess to internal carbon that is added to the composite pellet. External fuel that is required in order to supplement the heat for the process after producing heat by post combustion of CO generated from the direct reduction at RHF is also tabulated in Table 6. Excess fuel has been represented by carbon equivalent based on net calorific value of carbon at 328,000 kJ/kg of carbon. It is observed that for three layer bed, carbon equivalent, expressed as moles of carbon per mole of Fe₂O₃, is 0.95 compared to 1.25 and 1.35 required for two and three layers' bed. It is to

Fig. 7 Extrapolated temperature variation at six different vertical positions within the pellet bed of height 30 mm with reduction zone at 1,200 °C (online version in colour)

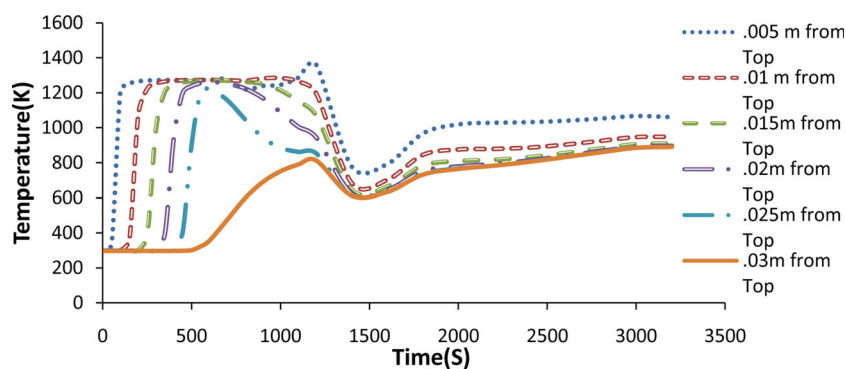


Table 6 Thermal efficiency at different layers of the pellet bed reduced at 1,200 °C at RHF

Depth of bed(m)	Average temperature of the bed (K)	Sensible heat (kJ/mol Fe ₂ O ₃)	Chemical heat (kJ/mol Fe ₂ O ₃)	Total heat	Theoretical heat (kJ/mol Fe ₂ O ₃)	Efficiency (%)	Heat generation by post combustion of CO (kJ/mol of Fe ₂ O ₃)	Carbon equivalent of external fuel required (mol/mole of Fe ₂ O ₃)
0.03	989	218	476	707	464	66	333	0.95
0.02	1,239	340	487	824	464	56	333	1.25
0.01	1,453	379	486	865	464	54	333	1.35

be noted that stoichiometric carbon required is 3 mol of carbon per mol of Fe₂O₃ and thus total carbon equivalent required are 3.95, 4.25 and 4.35 for single, double and triple layer bed, respectively.

3.5 Conclusions

1. A mathematical model has been developed to estimate the rate parameters for all three elementary steps of iron oxide conversions (hematite to magnetite to wustite to iron) during reduction of three layer iron ore–coal composite pellet bed at RHF based on experimental data. Subsequently, the model has been used to predict the evolution of various phases of iron oxide, metallic iron, and temperature in the pellet bed.
2. Model predictions indicate that total time of reduction of three layer pellet bed varies significantly with temperature between 1,200 and 1,300 °C. While the reduction time is 48 s in case of 1,200 °C, it could be merely 11 min at 1,300 °C.
3. Thermal efficiency (defined as theoretical minimum heat to total heat absorbed) calculated based on the model predictions, indicates maximum efficiency lies with the pellet bed of three layers and least for the single layer bed.
4. External fuel in addition to carbon supplied within the pellet bed measured in terms of carbon equivalent is found to be 3.95, 4.25 and 4.35 for single, double and triple layer bed respectively.

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