MODELING THE IRON ORE PELLETS REDUCTION ON SHAFT FURNACE PROCESS

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Abstract. *In this paper, a numerical model based on transport equations of momentum, energy and chemical species for gas and solid phases is proposed to simulate the inner phenomena in the direct reduction of the shaft furnace process. The model is verified using industrial data of productivity, raw materials and final composition of the briquettes. Thus, the model is used to study new operational practices regarding the availability of new raw materials and reducing gas in the process. In this study, three cases were considered which correspond to available raw materials commercialized by different suppliers. The effects on the gas and solid inner temperatures distributions, pressure and phases compositions are quantified based on the model predictions. The model, therefore, is an excellent tool for supporting the direct reduction (DRI) producers to select the appropriated raw materials, which best attain their needs.*

Keywords: *Multiphase model, pellets, shaft furnace, reduction*

1. INTRODUCTION

The shaft furnace process is used in several industries for processing granular materials due to its flexibility, scale and economic aspects. In general, the iron direct reduction processes use large amount of energy and raw materials, which depends particularly on the ores and pellets types and the shaft furnace operating conditions. Process modeling using advanced computers has been proven to be successful in increasing the efficiency of direct reduction plant operations by demonstrating the effects of process alternatives and expediting the decision-making process as well helping the adequate selection of raw material.

The field of non-catalytic, gas reaction modeling has been and is a very active research area in chemical engineering and process metallurgy fields [Austin et al, 1997, Yagi, 1993, Castro et al 2000, 2011, 2013, Dong et al, 2014, Kuang et al, 2014]. Several attempts have been in order to develop mathematical models of the direct reduction shaft furnace [Dong et al, 2014].

One of the most important application in the industrial scale is the reduction of iron oxides. In this work, a comprehensive mathematical model for the direct reduction of iron oxides in the shaft furnace has been developed and used to simulate the steady state of commercial shaft furnace for pellets reduction. The model is used to predict the productivity and efficiency of the gas shaft furnace. The effects of all external parameters such as the reducing gases flow rate and temperature, ore types and their characteristics on the process behavior can be examined in order to determine the optimum operating conditions of the shaft furnace for direct reduction of pellets in commercial plants. The model is used to study self-catalytic reforming in the transition zone.

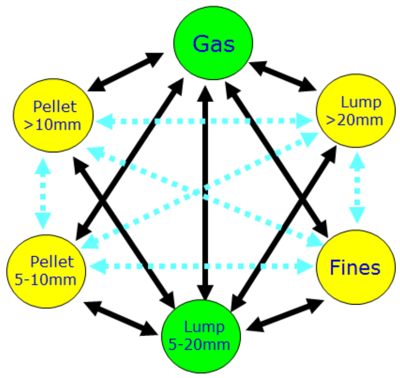
2. MODELING THE DIRECT REDUCTION ON SHAFT FURNACE

The shaft reduction process involves complex phenomena of momentum, energy and mass transfer. Usually, the direct reduction of shaft furnace is divided into 3 zones. The reduction, transition and cooling zones. In the reduction zone, the major reactions of solid gas are mainly controlled by the heat supply and local gas composition. In the transition zone, the reducing gas is fed at temperatures around 1100 ºC and the final reduction step usually takes place.

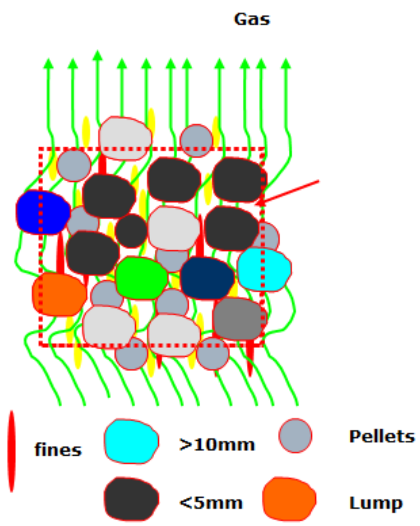
To successfully model the direct reduction process detailed rate equations for the reduction steps and heat transfer mechanism are need. In the transition zone new opportunities for improvement on heat efficiency by using some amount of oxygen injection with partial combustion of the hydrogen releasing energy for burden heat and endothermic reactions in the reduction zone.

2.1 Model features

The multiphase concept is used to model the direct reduction shaft furnace process. In this model, the pellets are treated by assuming different range of size distribution casting into classes of representative average size as a particular phase interacting with the others and the gas phase exchanging momentum energy and mass. For each of these phases, velocity, temperature and concentration fields are considered while the gas phase is assumed as a continuum with a pressure field.



a) Concept of phase interactions



b) Packed bed control volume concept

Figure 1 Multiphase modeling concept applied for the packed bed composed of different classes of pellets and lump ore

Figure 1 shows the modeling principles for the multiphase multicomponent formulation used in this study for treat the packed bed composed of pellets of different diameters and lump ore with the gas flow through the arrange of particles. The phase interactions are considered using momentum interaction for individual gas-solid packed bed and the heat transfer is computed for each individual granular materials. The chemical reactions take into account the individual characteristics of the granular materials. The rate equations considered in this model can be found elsewhere [Yagi, 1993, Austin et al, 1997, Castro et al, 2011].

2.2 Mathematical formulation

The mathematical model is based on transport equations for momentum, energy and mass conservations. The model is formulated assuming the size and composition distributions for several classes of pellets with their own reduction kinetics laws. The heat transfer is considered convective and conduction simultaneously taking place within the bed structure. The general equations are presented for the solid phases classes and gas separately.

Granular classes momentum conservation:

$$\frac{\partial\left(\rho_i \varepsilon_i u_{i,k} u_{i,j}\right)}{\partial x_k} = \frac{\partial}{\partial x_k}\left(\mu_s \frac{\partial u_{i,j}}{\partial x_k}\right) + F_j^{i-l} + F_i^{l} \tag{1}$$

Mass conservation of solid fractions:

$$\frac{\partial\left(\rho_i \varepsilon_i u_{i,k}\right)}{\partial x_k} = \sum_{m=1}^{Nreacts} M_n r_m \tag{2}$$

Enthalpy balance for solid fractions:

$$\frac{\partial\left(\rho_i \varepsilon_i u_{i,k} H_i\right)}{\partial x_k} = \frac{\partial}{\partial x_k}\left(\frac{k_i}{C_{p_i}} \frac{\partial H_i}{\partial x_k}\right) + E^{i-l} + \sum_{m=1}^{Nreacts} \Delta H_m r_m \tag{3}$$

Chemical species of solid phases

$$\frac{\partial\left(\rho_i \varepsilon_i u_{i,k} \phi_n\right)}{\partial x_k} = \frac{\partial}{\partial x_k}\left(D_n^{eff} \frac{\partial \phi_n}{\partial x_k}\right) - \sum_{m=1}^{Nreacts} M_n r_m \tag{4}$$

Gas momentum transfer

$$\frac{\partial\left(\rho_g \varepsilon_g u_{g,k} u_{g,j}\right)}{\partial x_k} = \frac{\partial}{\partial x_k}\left(\mu_g \frac{\partial u_{g,j}}{\partial x_k}\right) - \frac{\partial P}{\partial x_j} - F_j^{i-l} \tag{5}$$

Mass conservation of the gas phase:

$$\frac{\partial\left(\rho_g \varepsilon_g u_{g,k}\right)}{\partial x_k} = -\sum_{m=1}^{Nreacts} M_n r_m \tag{6}$$

Enthalpy conservation of gas phase:

$$\frac{\partial\left(\rho_g \varepsilon_g u_{g,k} H_g\right)}{\partial x_k} = \frac{\partial}{\partial x_k}\left(\frac{k_g}{C_{p_g}} \frac{\partial H_g}{\partial x_k}\right) - E^{g-p} - \sum_{m=1}^{Nreacts} \Delta H_m r_m \tag{8}$$

Chemical species

$$\frac{\partial\left(\rho_g \varepsilon_g u_{g,k} \phi_n\right)}{\partial x_k} = \frac{\partial}{\partial x_k}\left(D_n^{eff} \frac{\partial \phi_n}{\partial x_k}\right) + \sum_{m=1}^{Nreacts} M_n r_m \tag{9}$$

Semi empirical relations for the gas solid momentum transfer:

$$F_j^{g-i} = \left[1.75\rho_g + \frac{150\mu_g}{\left|\vec{U}_g - \vec{U}_i\right|}\left(\frac{\varepsilon_i}{d_i \varphi_i}\right)\right]\left(\frac{\varepsilon_i}{\left(1-\varepsilon_i\right)^3 d_i \varphi_i}\right)\left|\vec{U}_g - \vec{U}_i\right|\left(u_{g,j} - u_{i,j}\right) \tag{10}$$

Effective energy transfer among solid phases and gas:

$$E^{g-i} = \frac{6\varepsilon_i}{d_i\varphi_i}\frac{k_g}{(d_i\varphi_i)}\left[2+0.39\left(\frac{\rho\left|\vec{U}_g\right|}{\mu_g}(d_i\varphi_i)\right)^{1/2}\left(\frac{\mu_g C_{p,g}}{k_g}\right)^{1/3}\right](T_g - T_i) \tag{11}$$

$$\varepsilon_g = 1 - \sum \varepsilon_i \tag{12}$$

Where ε_i stands for the individual solid volume fractions of the pellets classes and ε_g is the gas volume fractions, k is the thermal conductivity d_i is the average particle diameter of the pellet class. The indexes i represent the classes of the pellets considered in the solid charged. The indexes j and k are for coordinates component direction n is chemical species and m the indicator of the reactions, M is the molecular weight of the species, P is gas pressure, F is component of momentum interactions among the phases and ***r*** is the rate of chemical reactions. ρ,ε,Cp, k and ΔH are phase density, volume fractions, heat capacity, heat conductivity and heat due to chemical reactions, respectively.

The quantity $E^{i\text{-}l}$ is the heat transfer among the phases and accounts for convective and radiation heat transfer. The gas-solids momentum interactions are represented by $F^{i\text{-}l}$ for each coordinate direction, given in Eq. (10). The above equations coupled with the rate of chemical reactions of reduction based on the 3-interface model for H_2 and CO [Castro et al, 2000, 2001, 2011] and the rate equations for self-reforming reactions are solved simultaneously. In the cooling zone, the carburization of the DRI is considered as first order controlled by the carbon deposition from the methane.

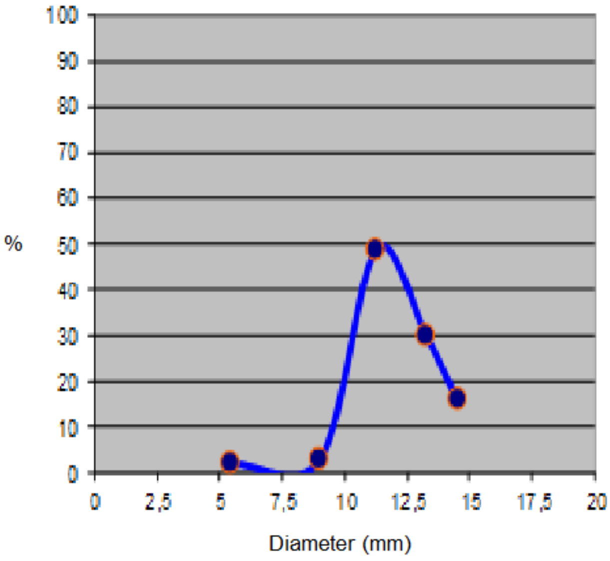
2.3 Numerical method

The set of differential equations, Eqs. (1)-(9) are solved numerically using the finite volume method. The gas velocity and pressure field coupling are solved using the SIMPLE algorithm. For all equations, the discretized algebraic equations are determined using the power law scheme [Patankar et al, 1972, Karki et al, 1988, Mealaen, 1992].

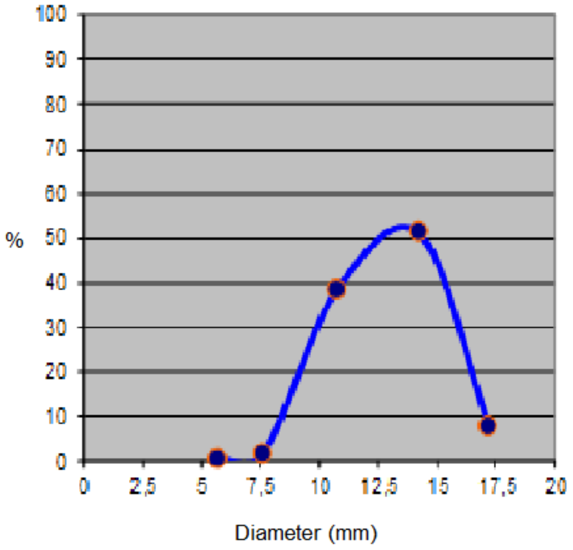
The system of algebraic equations were solved using the line-by-line iteration method based on the tri-diagonal algorithm. The convergence criterion was assumed the maximum error of 10^{-5} for the momentum and energy equations in addition to a mass balance of the individual species less than 1%. The numerical grid was selected by continuously refinement until the average error reach less than 1%.

3. RESULTS

The results presented in this paper aims to demonstrate the effect of two pellets distributions on the inner distributions of the shaft reactor.



a) Base case



b) New distribution

Figure 2 Classes of diameter distributions for two raw materials produced for direct reduction process based on shaft furnace

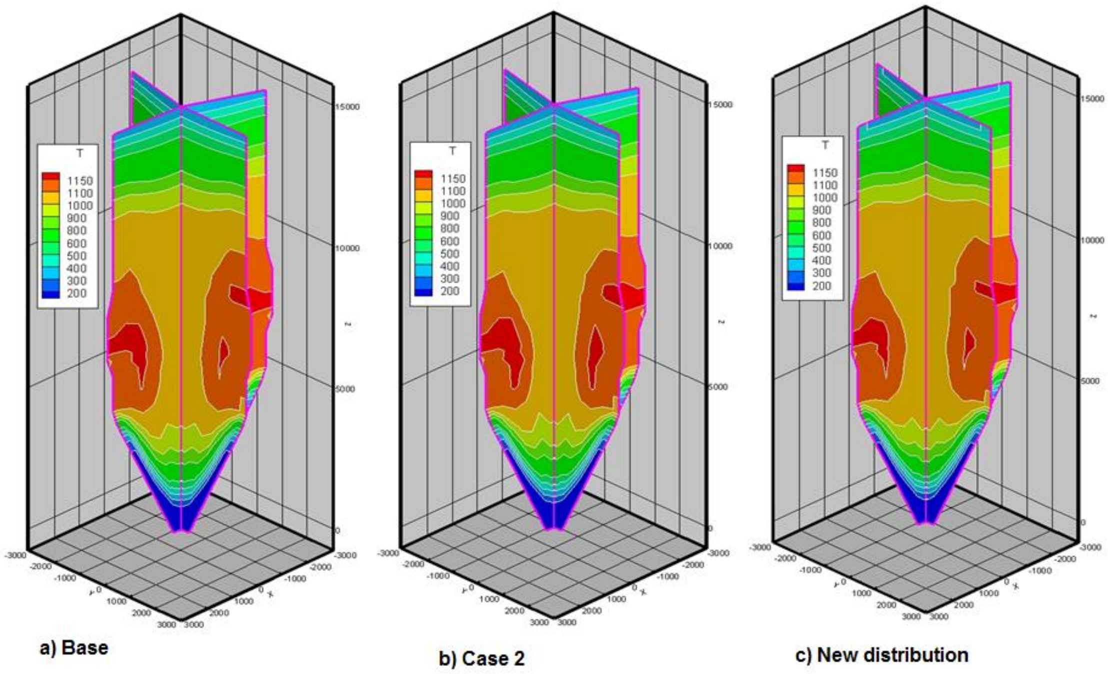


Figure 3 Inner temperature distributions for the cases analyzed in this study

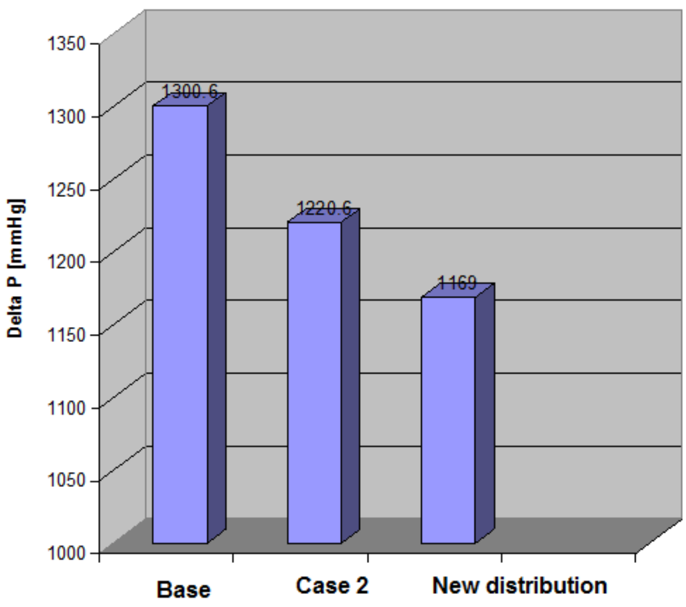


Figure 4 Pressure drop within the packed bed due to size distributions of the raw materials

The quality of the pellets regarding the reducibility is similar and the averaged size is different for each of the pellets with different fractions, which leads to temperature distributions patterns reflecting these distributions.

This feature of the model is only captured by the formulation presented in this study, since most of the models presented in the literature only consider the average size of the pellets. Figure 2 shows the granulometric distributions of the direct reduction pellets used in this study. As observed the new distribution show wilder range with the classes fractions above 15 mm around 30% which facilitates the gas flowing through the packed bed but, on the other hand, slow down the reaction kinetics and the heat transfer from the gas to the solid fractions as a whole. Figure 3 shows the temperature distributions of the shaft furnace for three representative cases of analysis of this study.

The average temperature distributions showed similar pattern with the effects of size distribution of the raw materials. The negative effect of increasing the fractions of the higher particle diameters classes were compensated by the increasing the gas flow rate due to decreasing the pressure drop through the bed.

Figure 4 shows the pressure drop of the entire reduction zone for the cases selected that confirms the gas distributions for compensating the deleterious effects of increasing the fractions of the higher diameters classes on the heat transfer by increasing the flow rate without increasing the pressure bed.

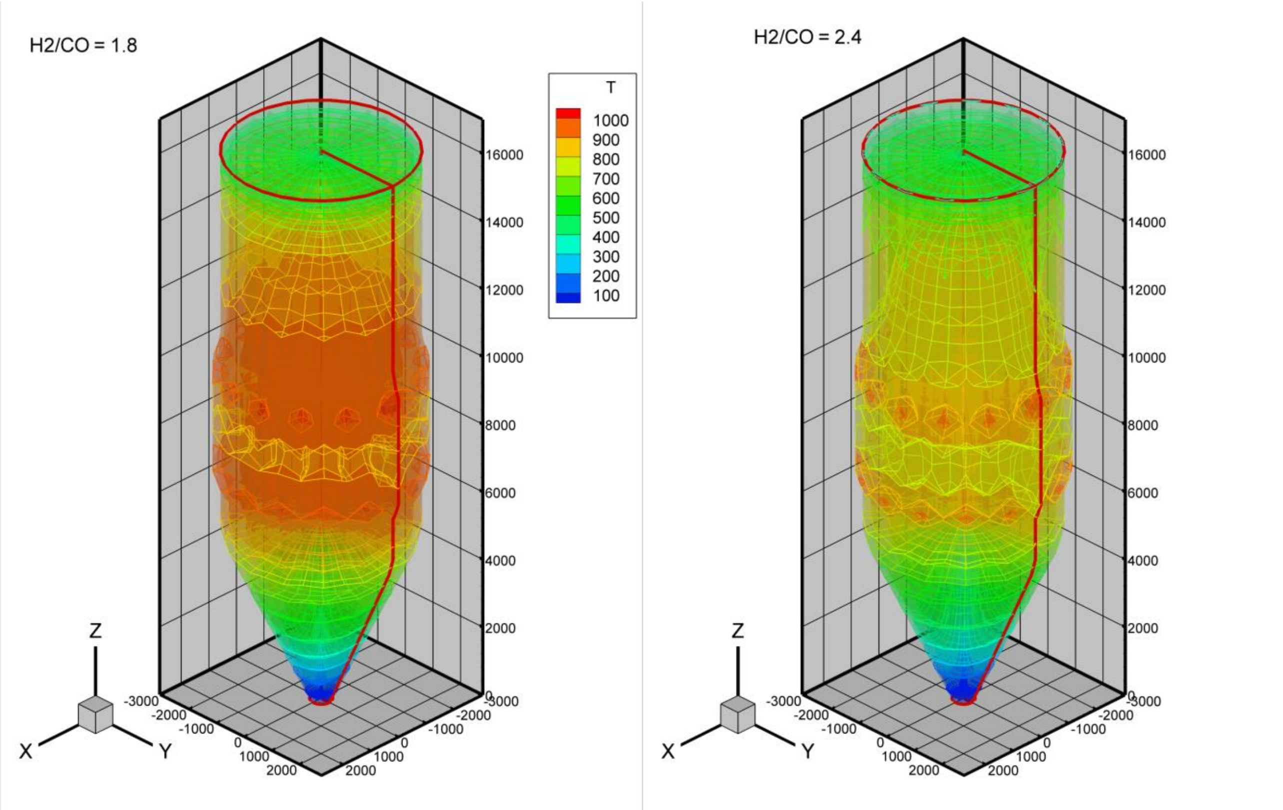


Figure 5 Effect of reducing gas composition on the internal state of the temperature distribution with self-catalytic reforming and 1.5% of oxygen injection

The effect of using new gas compositions for bustle injection on the transition zone is presented in Fig. 5. As the ratio of hydrogen to carbon monoxide increases the temperature decrease which can be compensated with injection of small amount of oxygen and methane in the transition zone.

This operational technique decrease around 20% of the specific emissions of CO_2 due to the replacement of the direct reduction using CO gas by H_2. This model has been used to design new operational conditions that contribute to make the direct reduction process cleaner and with higher energy efficiency.

4. CONCLUSIONS

This paper analyzed the shaft furnace for direct reduction as a multiphase multicomponent momentum, energy and mass transfer reactor by applying a comprehensive mathematical model. The effect of process variables and raw materials were investigated.

The model indicated that further improvements on the energy efficiency and environmental benefits could be obtained by using self-catalytic reactions and compensation of the heat supply using partial combustion of natural gas with oxygen.

5. ACKNOWLEDGEMENTS

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