Original Article

Study of the induration phenomena in single pellet to traveling grate furnace

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The process for pelletizing iron ore fines is an important operation unit for producing high quality of raw materials for the subsequent reduction processes such as blast furnace or direct reduction. The process essentially involves production of green pellets and induration on a traveling grate furnace to promote inner partial melt and agglomeration that confers adequate physical and metallurgical properties. This work focuses on the phenomena that occur in the firing step aiming the construction of a mathematical model that describes each phase and chemical species. The model was formulated based on transport equations able to predict the evolution of the temperature profile inside the pellet for each zone on the induration furnace. It was taken into account coupled phenomena of momentum, energy and mass transfer between gas and particles within the agglomerates. The finite volume method was used to discretize the transport equations of momentum, mass and energy describing the behavior of a pellet in an industrial traveling grate furnace. Model results are shown for the temperature profile along the pellet radius during the residence time inside the furnace. In this context, in the present work a tool was developed to optimize the thermal profile in the induration furnace and hence control the mechanical strength of the agglomerate.

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Abbreviations: $A_i$, surface area of solid materials; $C_p$, heat capacity; $D_{ij}$, binary diffusivity; $\bar{E}_i$, convective heat transfer; $\bar{F}_i$, momentum transfer; $H_i$, enthalpy of phase $i$; $\Delta H_i^j$, heat of formation of specie $j$ in phase $i$; $h_{ij}$, heat transfer coefficient; $k_i$, thermal conductivity of phase $i$; $M_j$, molecular weight of specie $j$; $P_i$, pressure of phase $i$; $R$, gas constant; $R_n$, rate of reaction $n$; $T_i$, temperature of phase $i$; $\bar{U}_i$, velocity vector of phase $i$; $\bar{W}_{ij}$, Weber number; $\bar{e}_i$, volume fraction of phase $i$; $\rho_i$, density of phase $i$; $\phi_i$, dependent variable in Eq. (2.1); $\varphi_i$, shape factor for phase $i$.

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1. Introduction

The ultra-fine fraction of iron ore produced in the beneficiation operations has motivated the development of agglomeration processes to produce raw materials suitable for using in blast furnace and reduction processes. The pelletizing process is one of the most important steps to furnish agglomerates of high quality with additional benefits of recycling the ultra fines within the steelmaking industry. This process involves two steps, the “green pellets” formation with the addition of binder to enhance agglomeration phenomena, and then the pellets follow to induration furnace, to attain mechanical resistance and appropriate the metallurgical characteristics required in the ironmaking facilities. The induration process using traveling grate can be divided into 4 different stages: drying, heating, firing and cooling zones [1]. The first step ensures that the pellets are fully dried with controlled velocity in order to keep the integrity of the pellets and forms the initial bonding phases. In the heating zone the temperature is increased and the reactions of carbonates decomposition start. These reactions continue in the next zone, firing zone, and additional partial melt among the particles occurs, depending on the heat input. The cooling zone stops theses reactions due to the drop in temperature and promotes resolidification and final cooling.

Fig. 1a shows a schematic view of these zones and Fig. 1b shows a typical temperature profile in each zone of the furnace.

The gas flow in each zone is sucked in the system by fans. The blow temperature should be controlled for better pellet quality and grate bars protection avoiding super heating [2], this control is carried out by using combustors and pos combustors of the fuels for each zone, where exhaust gases are usually used to account for better energy utilization. As consequence, the pellets of each layer are subjected to different thermal conditions inside the zones of the furnace (Fig. 2). This transient conditions imposed on the surface of the pellets develops temperature gradients inside the pellets which plays important role on the mechanical and metallurgical properties required in the following reduction steps such as blast furnace or direct reduction. Depending on the subsequent reduction process, specific quality of the fired agglomerate is required. Therefore, for each product, attention on the inner temperature of pellet is needed in order to attain quality and at the same time optimize the energy consumption of the overall process.

The inner phenomena that take place in the pellets accounts for heat, momentum and mass transfer, which are strongly affected by the rate of chemical reactions within the agglomerates [3]. In order to address these phenomena the rate equations are formulated for individual particles set and individual kinetics of the each “pellet feed” inside the agglomerate is considered for a representative control volume depending on the local gas flow and chemical species reacting within the pellet. The focus of the present work was the induration of pellets in traveling grate furnace to provide the inner pellets temperature profile traveling on the induration furnace, in order to support process analysis, optimization and control in pelletizing process. The temperature profile and thus, the thermal gradients developed for the representative pellets can be predicted. In this study, three representative pellets of 8, 12 and 15 mm were considered to take into account the granulometric distribution of the pellets charged and correspondent transient boundary conditions representing the conditions on each furnace zones.

![ Fig. 1 – (a) Scheme of the pelletizing furnace in a Traveling Grate system, (b) average temperature profile pellet with different sizes characteristics along of residence time in the furnace [1].](image-url)
2. Modeling

This model describes the temperature profile of single pellets traveling through the drying, heating, firing and cooling zones of a pelletizing furnace with moving grate. The model uses the measured operational parameters as input data to impose the transient boundary conditions along the furnace, as presented in Table 1.

The numerical domain considered in this model was the inner pellet coupled with the furnace environment by using the furnace temperature and gas flow as boundary conditions for the surface of the pellet. Therefore, Fig. 3 shows a slice of a pellet discretized in spherical coordinate system and the surface nodes used to impose transient boundary conditions. The thermo physical and chemical phenomena that occur inside the pellet during the induration process were considered in this model as the gas solid contact, gas flow, grate motion and phase transformations coupled with heat and mass transfer within the particles that forms a packed bed inside the pellet. The pellet in the furnace is represented by a porous sphere composed of particles which is in direct contact with the gas over the entire length of the furnace.

The transport equations were discretized for the domain representing the pellet using the finite volume method with the velocity and pressure fields for gas flow calculated using the SIMPLE algorithm coupled with the temperature and chemical species fields. Therefore, it was obtained in this model the inner temperature profile in the radial direction, gas velocity and composition, besides the temperature of the solid particles. Each chemical species is resolved by chemical reactions that allow the mass transfer between the phases. The model is composed of coupled solution for the rate equation of chemical reactions, momentum and energy transport equations. The Eqs. (1)–(4) represent, respectively, the momentum, mass, energy and chemical species balances:

\[
\frac{\partial (\rho u_i)}{\partial t} + \text{div} (\rho u_i U_j) = \text{div} (\varepsilon_i \text{grad} (u_j)) - \text{grad} (\varepsilon_i P) + F_i^\text{\(n\)}
\]

\[
\frac{\partial (\rho \varepsilon_i)}{\partial t} + \text{div} (\rho \varepsilon_i U_j) = \sum_{n=1}^{\text{reactions}} R_i^\text{\(n\)}
\]
Table 2 - Phases and chemical species for modeling.

<table>
<thead>
<tr>
<th>Phases</th>
<th>Chemical species (ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas</td>
<td>CO, CO₂, O₂, H₂, H₂O, N₂, SiO</td>
</tr>
<tr>
<td>Solids</td>
<td>Ore Fe₂O₃, Fe₃O⁴, FeO, Fe, CaO, Al₂O₃, MgO, SiO₂, H₂O, gangue</td>
</tr>
<tr>
<td>Partial molten</td>
<td>Fluxants Fe₂O₃, Fe₃O₄, FeO, Fe, CaO, Al₂O₃, MgO, SiO₂, H₂O, gangue</td>
</tr>
<tr>
<td></td>
<td>Si, Fe, FeO, SiO₂, Al₂O₃, CaO, MgO, gangue</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
\frac{d(\rho_i v_i h_i)}{dt} + \nabla \cdot (\rho_i v_i \mathbf{U}_i h_i) &= \nabla \cdot \left( \frac{k_i}{C_{p_i}} \text{grad}(h_i) \right) \\
&+ \sum_{n=1}^{r} R_i^n \Delta h_i^n + \dot{E}_i^n \\
\frac{d(\rho_i \varepsilon_i)}{dt} + \nabla \cdot (\rho_i \varepsilon_i \mathbf{U}_i) &= \nabla \cdot \left( \varepsilon_i D_{\text{bulk}} \text{grad}(\phi_i) \right) \\
&+ \sum_{n=1}^{r} M_{\text{species}} \varepsilon_i R_i^n
\end{align*}
\]

Thus, the pellets can be treated as a porous media with the boundary conditions for gas flow, energy and mass transfer in the interior of the pellet imposed at the surface of the individual pellet by using an effective overall heat transfer coefficient and the composition of the surface gas given by the furnace atmosphere. The pellet is composed of particles with different sizes and composition [5] and thus, local variables of porosity and thermo physical properties can be considered in the model.

This model is assumed as a multiphase model due to the several phases considered and it was used to describe the phenomena of fluid flow, heat transfer and chemical species conservations constitutive relations to account for phase interactions are used. In this paper, it was considered the gas, solid, and partial molten phases that can be developed within the pellet along the furnace zones. Table 2 provides the chemical species present in this model.

The momentum, energy and mass exchanges were considered in the model by using semi-empirical correlations [3]. The momentum exchange was modeled by the modified Ergun’s equation [6] suitable for anisotropic packed bed which approximate the inner pellet structure.

\[
\frac{F_{i}^g}{d_{i}^g} = \frac{F_{i}^s}{d_{i}^s} = \left[ \sum_{m} F_{i} \right] \frac{U_{i} - U_{i}}{U_{i} - U_s}
\]

\[
F_{i} = 150 \mu_{g} \frac{1}{[U_{i} - U_{i}]} \left( \frac{\varepsilon_{i}}{1 - \varepsilon_{i}} \right) \left[ \frac{1}{(1 - \varepsilon_{i})d_{i}} \right] \left[ \frac{1}{(1 - \varepsilon_{i})d_{i}} \right]
\]

where \(g\) and \(s\) indicate the indexes to represent gas and solid phases, respectively, \(f_{i}\) is volumetric fraction of component \(i\) in solid phase, \(F_{i}\) is resistance of solid component \(i\) to gas flow, \(d_{i}\) is the particle diameter for phase solid and \(\varphi\) is shape factor for phase solid, “pellet feed”.

The heat exchange (\(Q_{i}^g\)) among the individual pellet and gas should be calculated from external effective heat coefficient among gas and pellet in the furnace conditions using Ranz–Marshall Correlation to convective heat transfer and Stefan–Boltzmann Law to radiation heat transfer [3]:

\[
Q_{i}^g = -h_{i} g A(T_{i} - T_{f}) - \alpha_{i} (T_{i}^{4} - T_{f}^{4})
\]

and

\[
h_{\text{eff}} = \frac{k_{g}}{d_{i}} [2.0 + 0.39(Re_{i} - 3)^{0.5} Pr_{i}^{1/3}]
\]

where \(A\) is the superficial area, \(T_{i}\) is the pellet temperature, \(T_{f}\) is the furnace temperature dependent of the position in bed, \(d_{i}\) pellet diameter, \(\varepsilon\) is emissivity (\(\varepsilon = 0.9\) [3], \(\sigma\) is Stefan–Boltzmann Constant (\(\sigma = 5.67 \times 10^{-8} J/m^2 K^4\)) and \(Re_{i}\) and \(Pr_{i}\) are dimensionless numbers Reynolds and Prandt, respectively, calculated using average value of the properties and velocity field of the gas in furnace position and of the pellet.

In order to model the heat transfer between gas and particles solid phases inner pellet, the energy source depends on the heat transfer coefficient among gas and particles solid phases, according Ranz–Marshall Correlation [3]:

\[
\dot{E}_{i}^g = h_{i} g \sum_{i} \frac{6\varepsilon_{i}}{d_{i} \omega_{i}} (T_{i} - T_{s})
\]

\[
= \frac{k_{g}}{d_{i}} [2.0 + 0.39(Re_{i} - 3)^{0.5} Pr_{i}^{1/3}] \sum_{i} \frac{6\varepsilon_{i}}{d_{i} \omega_{i}} (T_{i} - T_{s})
\]

where \(T\) represents the average temperature within the control volume occupied by particles solid and gas phases. \(Re\) and \(Pr\) are inner local modified dimensionless numbers Reynolds and Prandt, respectively, calculated using average value of the properties and velocity field within the pellet.

The mass transfer takes place in the pelleting furnace due to chemical reactions and phase transformations. Firstly the moisture is evaporated from the interior of solids where the vapor water diffusion through boundary layer plays important role. The rate equation, representing the moisture evaporation can be represented by Eq. (8).

\[
R_{i} = \left\langle A_{i} \frac{D_{i}^{T_{\text{ave}}}}{d_{i}} \Sigma_{i} \left( \frac{\rho_{i} \omega_{i} O_{i}}{M_{i} H_{2}O} - \frac{P_{i}}{RT_{g}} \right) \right\rangle_{\infty}^{m_{H_{2}O} O_{i}}
\]

Additional rate equation needed to take into account reduction and reoxidation and melting-resolidification can be considered as in Eqs. (9) and (10), depending on the direction
of the reactions, which depend on the local oxygen potential and temperature [3].

\[
R_{n_i} = \frac{A_i \rho_i}{\tau} \sum_{m=1}^{n_i} \alpha_{n,m} \left( k_{i} \frac{\alpha_{iCO, H_2}}{M_{iCO, H_2}} - \frac{\alpha_{iCO_2, H_2O}}{M_{iCO_2, H_2O}} \right)
\]

(11)

\[
R_{n_i} = \left( \frac{T_j - T_{moln_j}}{\Delta T_j} \right) \sum_{k=0}^{n_i} \sum_{j=0}^{M_j} \frac{F_k \theta_j^k}{\theta_j}
\]

(12)

3. Results and discussion

The “Multiphase Multicomponent Reactive Flow, Heat and Mass Transfer Program” developed in FORTRAN 95/2000 language was used to obtain numerical solution of equations describing the gas flow in the induration furnace and inside of the pellet, reaction rates and heat transfer, coupled with evolution of gas composition. For the simulations, pellets with different diameters were selected, with average sizes of 8, 12 and 15 mm, to account for the effect of pellet diameter on the temperature along the residence time within the furnace.

In the model it was possible to predict the average temperature distributions of the pellet during the induration process for each zone. Comparative predictions for different pellet diameters are presented in Figs. 4-7.

The evaporation process is limited by the heat transfer in the drying zone. When the heat transfer is abruptly increased the inner pressure of the vapor increase and can degraded the pellets, therefore in this region the heating rate must be controlled. In the final step, the temperature of the drying process is almost the same and is independent of the pellet diameter, indicating that internal phenomena are controlling the drying rate.

The external conditions for pellets with different diameters are the same in the overall process, the difference observed on temperature is only due to geometrical effect and takes place only on the beginning of the each zone.

In the firing zone, however, phase transformations take place and absorb heat. Although only at higher temperature these phenomena is important and the pellet rises the temperature at the beginning of this zone controlled by the inner heat transfer driven by radiation, conduction and gas solid convection. In the cooling zone the partial melted materials solidify releasing heat at the beginning and the final cooling is controlled by the external heat exchange with the cooling gas.

The results presented in this section illustrate the need of controlled operation of the external atmosphere mainly with regard to the temperature uniformity of each zone and the heat exchange in the steps for drying, heating, firing and cooling. Strict control of the heat transfer is, therefore, the key technological parameter to get suitable properties and optimize the consumption of fuel.

In order to verify the importance of the thermal gradients within the pellets and hence the impact of charging pellets of different diameters on the temperature distributions,
Figs. 8–10 compare the temperature distribution behavior along the pellet radius at beginning, middle and end of each zone for the pellets of 8, 12 and 15 mm, respectively. It is observed that the temperature patterns present similar behavior for all zones, although the temperature differences for surface and center of the pellets can be quite different, mainly due to the time need to the thermal front propagate and get uniform within the agglomerate structure, which in turn, is strongly dependent upon the inner gas path and agglomerate composition.

Fig. 8 – Temperature profiles within an individual pellet of 8 mm diameter along the furnace zones, (a) drying zone, (b) heating zone, (c) firing zone and (d) cooling zone.

Fig. 9 – Temperature profiles within an individual pellet of 12 mm diameter along the furnace zones, (a) drying zone, (b) heating zone, (c) firing zone and (d) cooling zone.
It is observed in Fig. 8 that as the temperature progress inward the pellet with 8 mm diameter, the gas flows through the pores and as time passes, the temperature became uniform due to the combined effect of heat conduction and inner convection. At the beginning of each zone, the surface of the pellets instantly reaches the gas temperature due to high external effective heat coefficient, which accounts for convective and radiation effects, in the interior of the pellet the conduction of the heat through the pores plays the major role and leads the center temperature of the pellet to remain lower. This pattern was observed for all zones and in the cooling region the temperature gradient is inverted.

Fig. 9 shows similar trend for the temperature pattern for pellets with 12 mm of diameter, although the rate of heating and cooling are strongly dependent on the pellet diameter.

Fig. 10 shows the temperature radial distribution for pellets with 15 mm of diameter. It was observed lower temperature gradient in the drying zone due to higher consumption of heat during the evaporation of water, indicating that the heat transfer within the pellet is the controlling mechanism for temperature increase, which was not observed for smaller pellets. For the other zones, the temperature pattern showed similar behavior although larger thermal gradient was observed, as expected.

These results confirmed the strong dependency of the suitable residence time for each granulometric range and suggests that narrow distribution will produce more uniform properties of the fired pellets and justify the production of strictly controlled green pellets.

4. Conclusions

A mathematical model able to predict the behavior of the average temperature of the pellets with different diameters in traveling grate furnace was developed. The inner temperature pattern for the pellets along the grate passing through the zones was predicted for the individual pellets. The model implementation and simulation procedure allowed to predict the temperature profile of each pellet traveling throughout the drying, heating, firing and cooling zones of the furnace and the temperature gradient along of the pellet radius was also shown. Numerical results for pellets with different diameters showed the impact of charging pellets with wider granulometric distribution in the furnace and indicated that the properties of the pellets could be significantly different since the thermal cycle of the individual pellets has strong effect on the phase transformations and induration phenomena. In this investigation it is concluded that pellets with narrow distribution would give moderate inner temperature gradient and hence it is expected to present suitable mechanical and metallurgical properties.

Conflicts of interest

The authors declare no conflicts of interest.
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