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STUDY OF THE INDURATION PHENOMENA OF A SINGLE PELLET IN THE TRAVELLING GRATE FURNACE[1]

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Abstract

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 proprieties. 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 is formulated based on transport equations able to predict the evolution of the temperature profile inside of the pellet for each zone on the induration furnace. It is taken into account coupled phenomena of momentum, energy and mass transfer between gas and particles within the agglomerates. The finite volume method is used to discretize the transport equations of momentum, mass and energy describing the behavior of a pellet in a industrial travelling grate furnace. Model results are shown for the temperature profile along of the pellet radius during the residence time. The model is a tool to optimize the thermal profile in the induration furnace in order to avoid crack formation and control the mechanical strength of the agglomerate.

Key words: Pellets; Agglomeration; Induration; Modeling.

ESTUDO DO FENÔMENO DE ENDURECIMENTO DA PELOTA INDIVIDUAL EM FORNO DE LEITO MÓVEL

Resumo

O processo de pelotização de finos de minério de ferro é uma importante operação unitária para a alta qualidade da matéria-prima para os subsequentes processos de redução tais como alto forno e processo de redução direta. O processo essencialmente envolve a produção de pelotas verdes e seu endurecimento em um forno de leito móvel para promover a fusão parcial das partículas internas e conferir propriedades físicas e metalúrgicas adequadas aos aglomerados. Este trabalho foca os fenômenos que ocorrem durante a etapa de queima visando à construção e um modelo matemático que descreve cada fase e espécies químicas. O modelo é formulado baseado nas equações de transporte capaz de prever a evolução no perfil de temperatura no interior da pelota para cada zona do forno de endurecimento. Levando em conta os fenômenos de momentos acoplados à transferência de energia e massa entre o gás e as partículas constituintes do aglomerado. O método de volumes finitos é usado para discretizar as equações de transporte de momento, massa e energia, descrevendo o comportamento da pelota em um forno industrial de leito móvel. Os resultados do modelo mostraram os perfis de temperatura ao longo do raio da pelota durante a residência no forno. O modelo é uma ferramenta pra otimizar o perfil térmico no forno de endurecimento com a finalidade de evitar a formação de fissura e controlar a resistência mecânica do aglomerado.

Palavras-chave: Pelotas; Aglomeração; Endurecimento; Modelamento.

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1 INTRODUCTION

The ultra-fine fraction of iron ore produced in the beneficiation operations drove to the development of agglomeration processes to produce raw materials suitable to use in blast furnace and reduction processes. The pelletizing process is one of the most important step 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 plants. The induration process using travelling 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. 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.(2) The cooling zone stops theses reactions due to drop in temperature and promotes resolidification and final cooling.
The Figure 1a shows separately the different zones and the Figure 1b shows a typical temperature profiles in each zone and is expected that significant differences on the temperatures due to the size of the pellets only take place at the beginning of each zones.

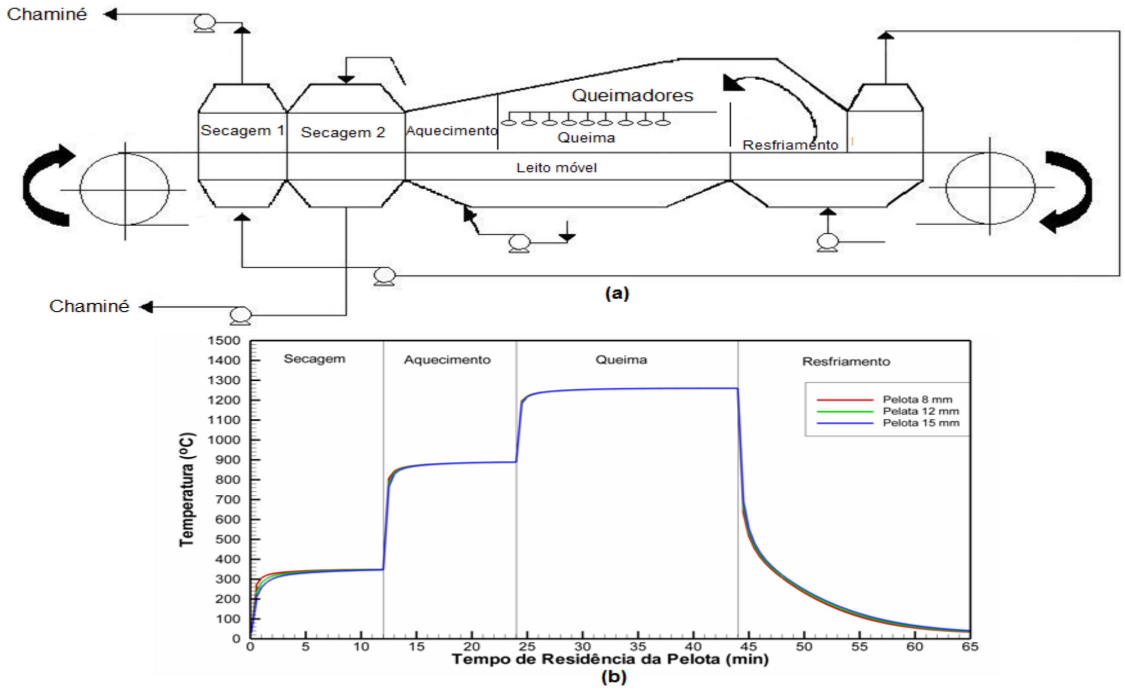

Figure 1 – (a) Scheme of the pelletizing furnace in a Travelling Grate system, (b) Average temperature profile among gas and pellet with different sizes characteristics along of residence time in the furnace.(1)

The gas flow in each zone is sucked in the system by fans.(3) The blow temperature should be controlled for better pellet quality and grate bars protection avoiding super heating. Therefore, attention on the inner temperature of pellet is needed in order to enhance the energy efficiency of the overall process.

The inner phenomena taking place in the pellets accounts for heat, momentum and mass transfer which are strongly affected by the rate of chemical reactions within the agglomerates. In order to address these phenomena the rate equations must be formulated for individual particles set and individual kinetics of the each *"pellet feed"* can be considered depending on the local gas flow and chemical species reacting within the pellet.(4) The focus of the present work is the induration of pellets in travelling grate furnace to provide the pellets temperature profile in each furnace zone, in order to support process analysis, optimization and control in pelletizing process.

2 MODELING

This model describes the temperature profile of single pellets travelling through the pelletizing furnace with moving grate. The thermo physical and chemical phenomena that occur during the induration process are the gas solid contact, flows, phase transformations coupled with heat and mass transfer.

The transport equations were discretized 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. 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 equations (1), (2), (3) and (4) represent, respectively, the momentum, energy, mass and chemical species balances:

$$\frac{\partial\left(\rho_i \varepsilon_i u_j\right)}{\partial t} + div\left(\rho_i \varepsilon_i \vec{U}_i\, u_j\right) = div\left(\varepsilon_i \mu_i\, grad\, \left(u_j\right)\right) - grad\, \left(\varepsilon_i P_i\right) - F_i^{\,k} \tag{1}$$

$$\frac{\partial\left(\rho_i \varepsilon_i\right)}{\partial t} + div\left(\rho_i \varepsilon_i \vec{U}_i\right) = \sum_{n=1}^{nreações} R_n^i \tag{2}$$

$$\frac{\partial\left(\rho_i \varepsilon_i h_i\right)}{\partial t} + div\, \left(\rho_i \varepsilon_i \vec{U}_i h_i\right) = div\left(\frac{k_i}{C_{P_i}} grad\, \left(h_i\right)\right) + \sum_{n=1}^{nreações} R_n^i \Delta h_n^i + \dot{E}_i \tag{3}$$

$$\frac{\partial\left(\rho_i \varepsilon_i \phi_{i,iespecie}\right)}{\partial t} + div\left(\rho_i \varepsilon_i \vec{U}_i \phi_{i,iespecie}\right) = div\left(\varepsilon_i D_{iespecie}^{bulk} grad\left(\phi_{i,iespecie}\right)\right) + \sum_{n=1}^{nreaçoes} M_{iespecie} R_n^i \tag{4}$$

The mathematical model of pellet induration process in travelling grate furnace is developed to predict detailed information including temperature inside of pellet along the radius along the time, which in turn, corresponds to the residence time within the furnace. In the formulation of the model, the following phenomena have been taken into account: (1) heat and mass transfer between the particles pellet and gas; (2) Oxidation magnetite; (3) phases transformations.

The following assumptions were made: (1) the pellet is composed of small particles known as "*pellet feed*, represented by the average size; (3) height of the pellet in bed remains constant during induration path; (4) the whole process occurs at the steady state, although the individual particles is subjected to a thermal cycle (Figure 1b).

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. In order to simulate the inner phenomena occurring in a representative pellet, a solid angle of the sphere is considered and a numerical grid is generated in spherical coordinates. Figure 2 outlines the geometry of the solid angle discretized to represent the pellet. Thus the pellets can now be treated as a porous media with the boundary conditions for gas flow, energy and mass transfer.

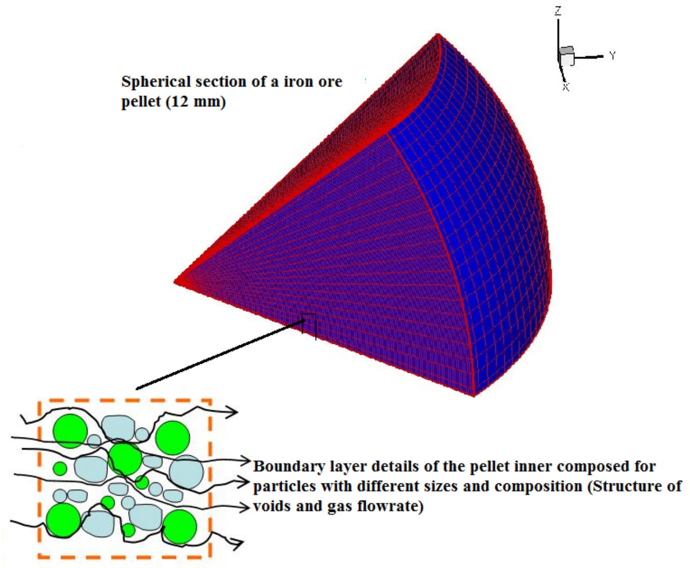

Figure 2 – Grid to simulation and boundary layer in the pellet inner.

The momentum, energy and mass exchanges are considered in the model by using semi-empirical correlations.(4) The momentum exchange is modeled the modified Ergun's Equation(4) suitable for anisotropic packed bed.

$$F_g^s = -F_s^g = \left[\sum_m f_m F_m\right]\left|\vec{U}_g - \vec{U}_s\right|\left(\vec{U}_g - \vec{U}_s\right) \qquad (5)$$

$$F_m = 150\mu_g \frac{1}{\left|\vec{U}_g - \vec{U}_s\right|}\left(\frac{\varepsilon_m}{(1-\varepsilon_m)d_m\varphi_m}\right)^2 + 1{,}75\rho_g\left(\frac{\varepsilon_m}{(1-\varepsilon_m)d_m\varphi_m}\right) \qquad (6)$$

Where *g* e *s* indicate the indexes to represent gas and solid phases, respectively, fm is volumetric fraction of component *m* in solid phase, *F* is resistance of solid component *m* to gas flow, *d* is the particle diameter for phase *solid and* φ is shape factor for phase solid (*pellet feed*).

In order to model the heat transfer between gas and solid phases, the average particle diameter Eq. (7) was applied:(5)

$$\dot{E}_g^s = -\dot{E}_s^g = \frac{k_g}{d_p}\left[2.0 + 0.39\left(Re_{g-s}\right)^{0.5}\left(Pr_g\right)^{1/3}\right]\sum_m \frac{6\varepsilon_m}{d_m\varphi_m}\left(T_g - T_s\right) \qquad (7)$$

Where *T* represents the average temperature in control volume to solid and gas phases. *Re* and *Pr* are modified dimensionless numbers Reynolds and Prandt, calculated using average value of the properties and local velocity fields.

The mass transfer takes place in the pelletizing furnace due to chemicals reactions and phase transformations. Firstly the moisture is evaporated from the solids with diffusion of the water vapor through of boundary layer playing important role. The rate equation, representing the moisture evaporation can be represented by Eq. 8.(4)

$$R_{18_i} = \left\langle A_i \frac{D^{T_{\mathrm{ave}}}_{\mathrm{H_2O,N_2}}}{d_i} Sh_i \left(\frac{\rho_{\mathrm{g}} \omega_{\mathrm{H_2O(g)}}}{M_{\mathrm{H_2O}}} - \frac{P_{\mathrm{H_2O,sat}}}{RT_{\mathrm{g}}} \right) \right\rangle_{-\infty}^{\dot{m}_{\mathrm{H_2O(i)}}} \tag{8}$$

Additional rate equation needed to take into account reduction and reoxidation and melting-solidification can be considered as in Eqs 9-10(4), depending of the direction of the reactions, which depend on the local oxygen potential and temperature.

$$R_{n_i} = A_i \frac{\rho_g}{W} \sum_{m=1,3} \alpha_{n_i,m} \left(K_m \frac{\omega_{\mathrm{CO,H_2}}}{M_{\mathrm{CO,H_2}}} - \frac{\omega_{\mathrm{CO_2},H_2O}}{M_{\mathrm{CO_2},H_2O}} \right) \tag{9}$$

$$R_{n_i} = \left\langle \frac{T_i - T_{\mathrm{melt}_{\phi_j}}}{\Delta T_{\phi_j}} \right\rangle_0^1 \frac{\sum_{\mathrm{face}} F^k \phi_j^k}{M_{\phi_j}} \tag{10}$$

3 RESULTS

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 inside the pellet, reaction rates and heat transfer, coupled with evolution of gas composition. For the simulation were selected pellets with different diameters, with average size of 8, 12 and 15 mm, respectively, to account for the effect of the pellet diameter on the temperature and composition along the residence time within the furnace.

In the model was possible to predict the average temperature between the pellet and gas during overall process. The Figures 3 to 6 present the comparative predictions of temperature distributions during the induration process for each zone.

It is observed that the temperature patterns presents similar behavior for all zones, although the temperature differences for surface and centre 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. In the drying the agglomerate temperature takes about 5 minutes to get uniform, depending on the pellet diameter and the temperature difference between the centre and surface is steeper for higher diameters. As can be observed, the evaporation process is limited by the heat transfer. 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 is controlled and almost uniform evaporation rate is observed at the end of this zone with the gas flow through the pellet structure playing important role. As can be observed, the final step of the drying process is almost same and is independent of the pellet diameter, indicating that internal phenomena are controlling the drying rate.

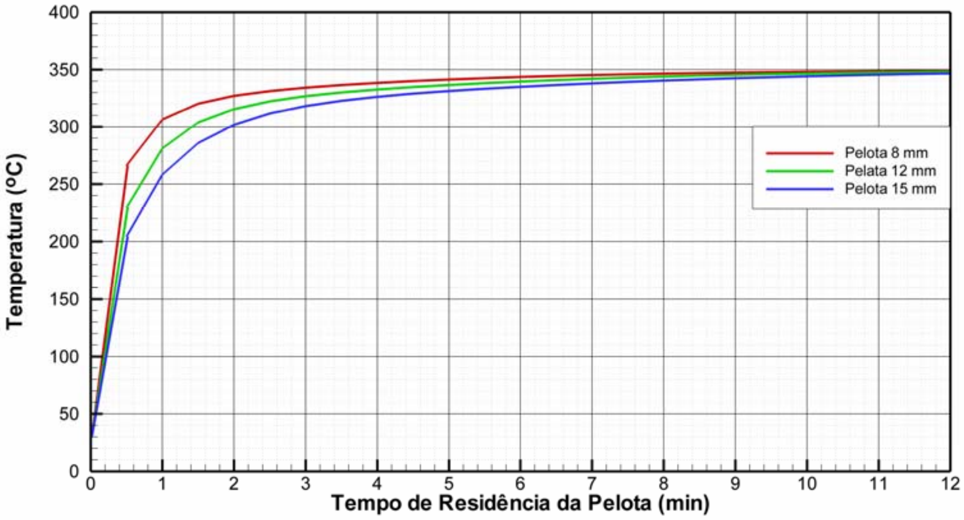

Figure 3 – Average Temperature Profile according to residence time of the pellet in the drying zone.

Figure 4 shows the average temperature distribution for the heating zone for different pellet diameters. As the external conditions are same, the difference observed on the temperature is only due to geometrical effect. For the firing zone, however, the phase transformations take place and absorb heat. Although only at higher temperature these phenomena are 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.

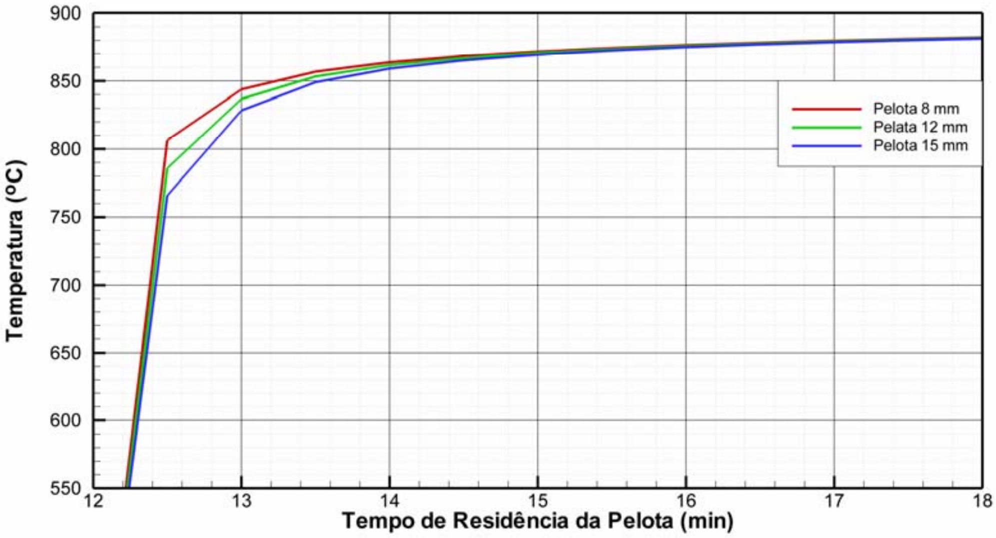

Figure 4 – Average Temperature Profile according to residence time of the pellet in the heating zone.

Figure 5 – Average Temperature Profile according to residence time of the pellet in the firing zone.

In order to verify the importance of the thermal gradients within the pellets and hence the impact of charging pellets of different diameters the temperature distributions along the pellet radius where shown for the beginning, middle and final position of each zones. Figures 7, 8 and 9 shows these results.

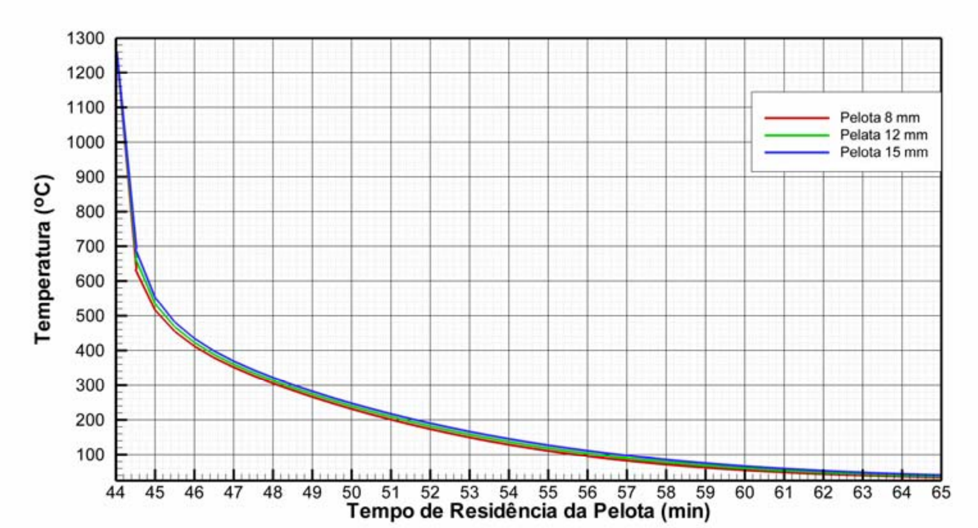

Figure 6 – Average Temperature Profile according to residence time of the pellet in the cooling zone.

The Figures 7, 8 and 9 compare the behavior of the pellet with different diameters, at beginning, middle and end of each zone for the pellets of 8, 12 and 15 mm, respectively. As can be observed, for the beginning of the zones the pellets of higher diameters develops higher thermal gradients, but for the final of each zone the thermal gradients are nearly null for all pellets analyzed.

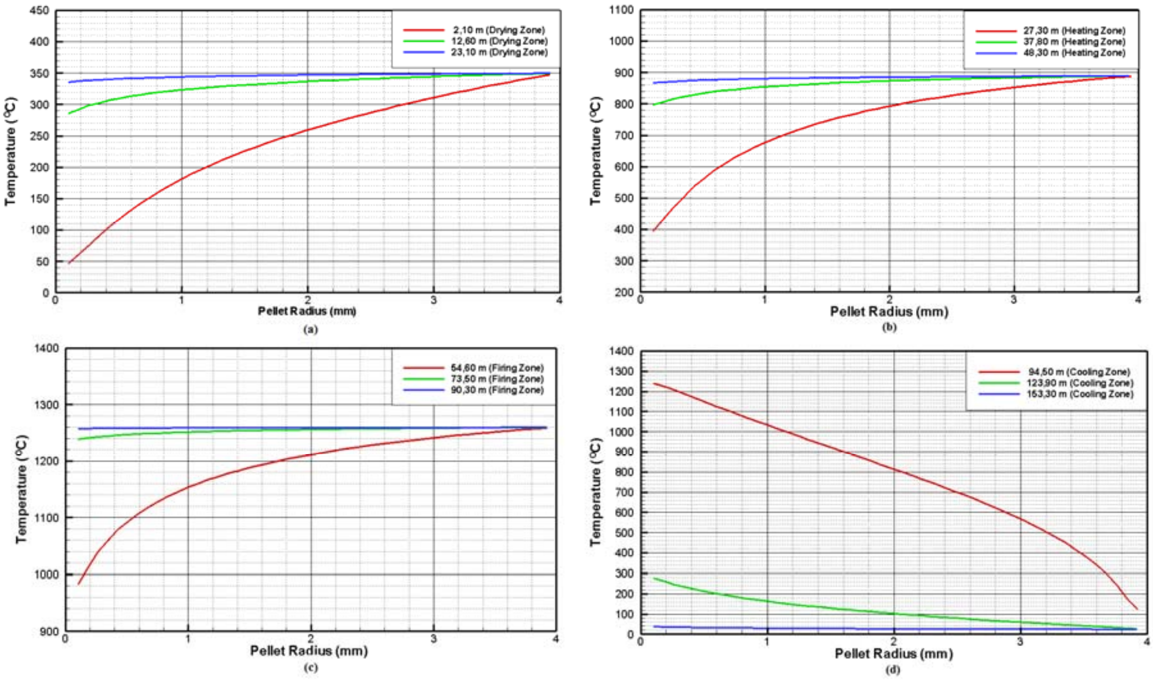

Figure 7 – Temperature profiles within an individual pellet of 8 mm diameter along the furnace zones, (a) drying zone, (b) heating zone, (c) firing zone and (d) cooling zone.

It is observed in Figure 7 that as the temperature progress inward the pellet with 8 mm the gas flows through the pores and as time is passed the temperature became uniform due to the combined effect of heat conduction and inner convection. At the beginning of each zone the surface of pellet 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 to the temperature center of the pellet to remain lower. This pattern is observed for all zones and in the cooling region the temperature gradient is inverted.

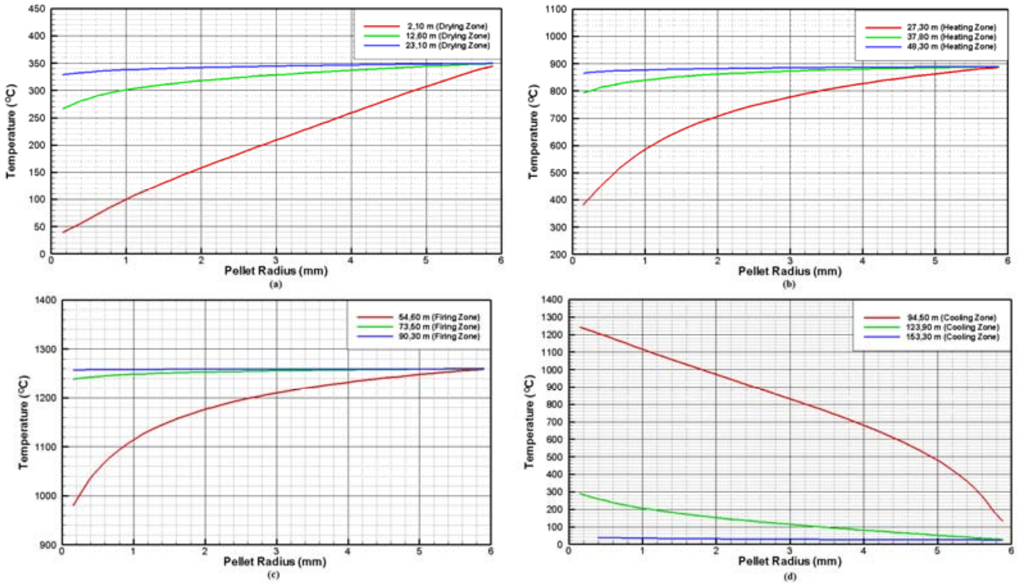

Figure 8 – Temperature profiles within an individual pellet of 12 mm diameter along the furnace zones, (a) drying zone, (b) heating zone, (c) firing zone and (d) cooling zone.

Figure 8 shows similar trend for the temperature pattern, although the rate of heating and cooling are strongly dependent on the pellet diameter. These results confirmed the strong dependency of the suitable residence time for each granulometric range and suggest that narrow distribution will produce more uniform properties of the fired pellets and justify the production of strictly controlled green pellets.

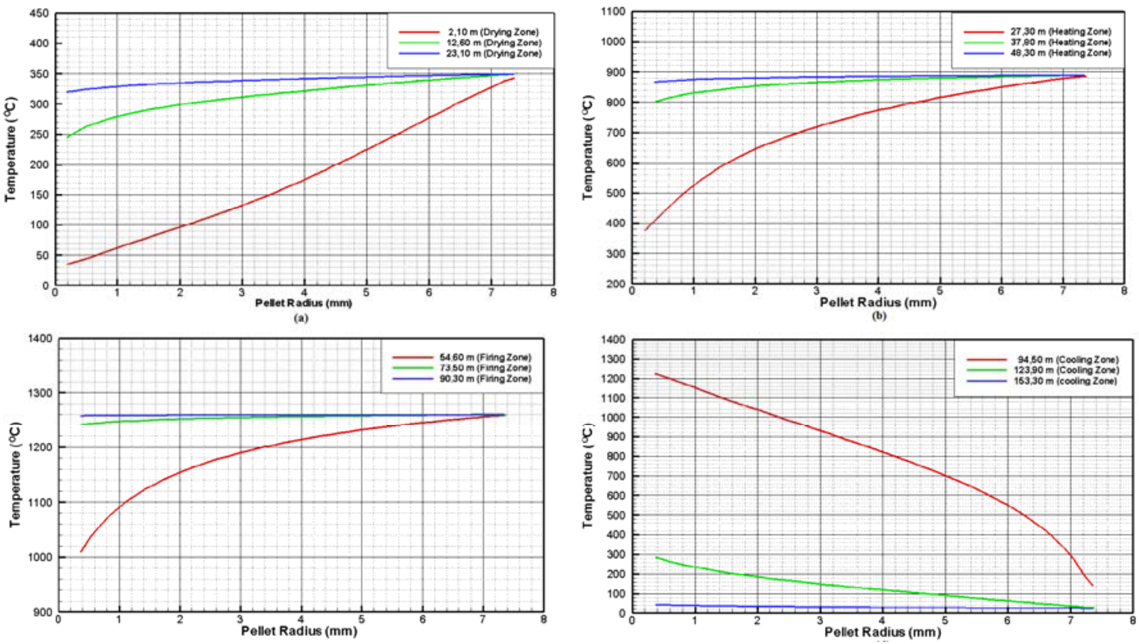

Figure 9 – Temperature profiles within an individual pellet of 15 mm diameter along the furnace zones, (a) drying zone, (b) heating zone, (c) firing zone and (d) cooling zone.

Figure 9 shows the temperature radial distribution for pellet with 15 mm of diameter. It is 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 is observed, as expected.

4 CONCLUSIONS

A mathematical model able to predict the behavior of the average temperature of the pellets with different diameters was developed. The inner temperature pattern for the pellets along the grate passing through the zones is predicted for the individual pellet. The model implementation and simulation procedure allowed to predict the temperature gradient of each pellet travelling through out the drying, heating, firing and cooling zones of the furnace and the temperature profile along of the pellet radius is 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 is concluded that pellets with 12mm with narrow distribution would give moderate inner temperature gradient and hence is expected to present suitable mechanical and metallurgical properties.

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