23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

A MULTIPHASE MODEL FOR SIMULATING NEW TECHNOLOGIES FOR THE IRON ORE SINTERING PROCESS

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Abstract. *The purpose of this research is to demonstrate new promising technologies able to use significant amount of biomass and gas fuels into the iron ore sintering process. The research was carried out using a comprehensive multiphase multicomponent mathematical model, which takes into account mutual interactions of momentum energy and chemical species using fundamental relationships for describing the momentum, energy and mass transfer simultaneously taking place within the sinter strand. The model is verified using pilot plant results and then was used to investigate proposal of new technologies. An industrial base case is simulated and global parameters are compared to verify the model validity. Thus, 3 new cases of new technologies are analyzed: a) Agglomerated biomass as solid fuel, b) Biogas hydrogen rich as fuel mixed with oxygen and c) A mix of biomass and biogas. The computational results indicated that the sintering process could be improved such as decreasing the specific* CO_2 *emissions, energy consumption and sinter quality represented by liquid phase formation and returned sinter.*

Keywords: *Multiphase model, sintering process, gas injection, biomass*

1. INTRODUCTION

The steel industry is a huge consumer of energy and natural resources such iron ores, limestone and coal. Thus, incremental improvements on the processes efficiency have large impact on the environment and economic benefits. In the integrated route of steel production, the sintering process plays important role furnishing high quality of raw materials for the blast furnace. Besides, this process is the most important for materials recycling within the steelworks due to its flexibility of using several sources of raw materials and energy. Many efforts have been made to decrease the fossil fuels utilization due to the environmental restrictions (Oyama et al, 2011, Guilherme et al, 2012). The process is complex and involves various physical and chemical phenomena such as heat, mass and momentum transfer coupled with chemical reactions (Yamaoka et al, 2005, Castro et al, 2012). These phenomena take place simultaneously increasing considerably the complexity of process analysis. Additionally, the iron ore sintering process plays important role on the task of sustainable use of the raw materials in the steel industry. In the conventional operation, the process is carried out in a moving bed where a mixture of raw materials is continuously charged and an ignition furnace is placed at the beginning of the sinter bed. The ignition furnace starts the fuel combustion at the top of the bed air is sucked passing through the materials and as it moves, a relative narrow band of ignition zone moves down through the bed, that can be strongly affected by the quality of the raw materials. Several chemical reactions and phase transformations are affected not only by the heat front modifications but also due to changes of local gas composition and initial melting temperatures of the mixture of raw materials. When local temperature and composition of the solids is reached, mostly the phase transformations are driven by heat supply and diffusion that take place within the particles with the mechanism of liquid formation playing the major role. The materials partially melt down when the local temperature reaches the melting temperature and as it moves, the contact with cold gas promotes the re-solidification and heat release that promotes the particle agglomeration forming a continuous porous sinter cake. Therefore, modeling these coupled phenomena is a challenge task. Some attempts to develop detailed microstructural analysis and to determine parameters for numerical simulations on the microscale level have been carried out. Kasai et al among others (Kasai et al., 2005) investigated the influence of the sinter structure into the macroscopic sinter properties. Several attempts to model the sintering process have been made, among others Yamaoka et al, Castro et al (Yamaoka et al., 2005, Castro et al., 2012, 2013, cummings et al., 1990) have proposed comprehensive mathematical models to predict the coupled phenomena within the sinter strand. Particularly, new technologies and materials recycling have been proposed in order to replace the fossil fuels and increase the amount of recycling with lower return sinter. However, the temperature distribution and the residence time of the materials at the higher temperature zone is lower, which may deteriorates the sinter quality. In order to overcome these phenomena, in this paper is proposed the gaseous injection combined with oxygen to allow complete replacement of coke breeze as fuel. The concept of gaseous injection into the sintering bed has been successfully applied and enhancement of the sinter properties related with reducibility and strength have been observed with further decrease of the return sinter (Guilherme et al., 2012 and Castro et al., 2012). One of the important features of the sintering strand is regard as the heat supply on the top region of the sintering layer, which implies in a non-uniform sinter product. This work purposes avoiding this phenomenon with additional injection of oxygen to early burnout the gas within the sintering zone (Oyama et al., 2011). To analyze this technology a comprehensive multiphase multi component mathematical model was adapted. A base case is used as reference and new simulations conditions based on biomass and gaseous fuels are analyzed.

2. METHODS

2.1 Model principles

The analysis is carried out based on a mathematical model composed by a set of partial differential equations representing the conservations of momentum, energy and chemical species for gas, solid phases (raw material mix and solidified liquid) and melting. The domain is restrict to the moving strand with the gas passing transversely through the bed. Figure 1 presents a flowsheet of the sinter plant where the auxiliary units of gas treatment, raw materials preparation and heat recovery system.

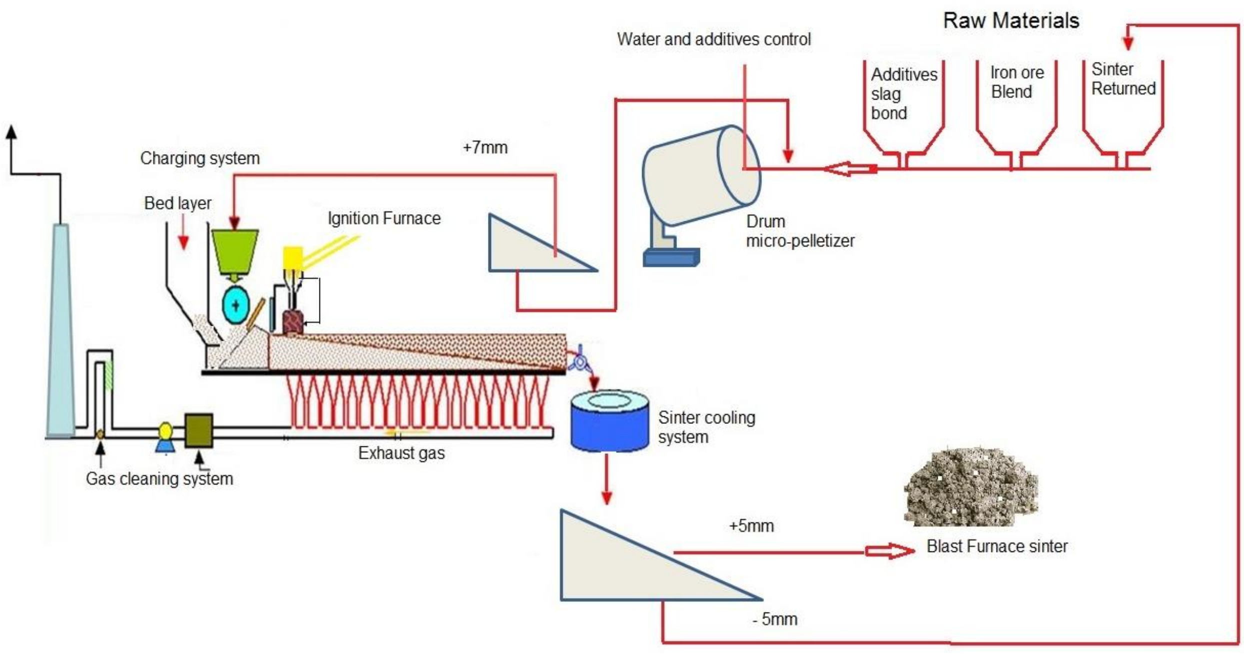


Figure 1 Overview of the sinter unit for integrated steelworks (Castro et al., 2012)

2.2 Mathematical formulation

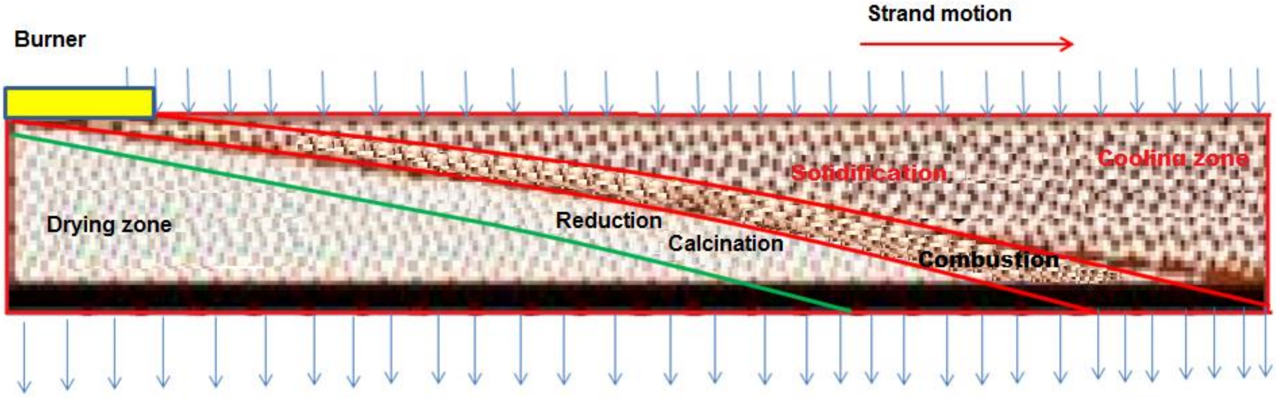
The model is focused on the control volume of the moving bed in an Eulerian reference frame. The conservation equations are formulated based on the momentum, continuity, energy and chemical species of the solid, gas and liquid phases. Equations (1)-(4) are solved in the physical domain shown in Fig. 2 (a) and Fig. 2 (b) presents a typical microstructure obtained in an industrial machine. The model equations are solved using the initial and boundary conditions of inflow, outflow, and impermeable wall with convective combined with radiation fluxes for energy equations.

Momentum:

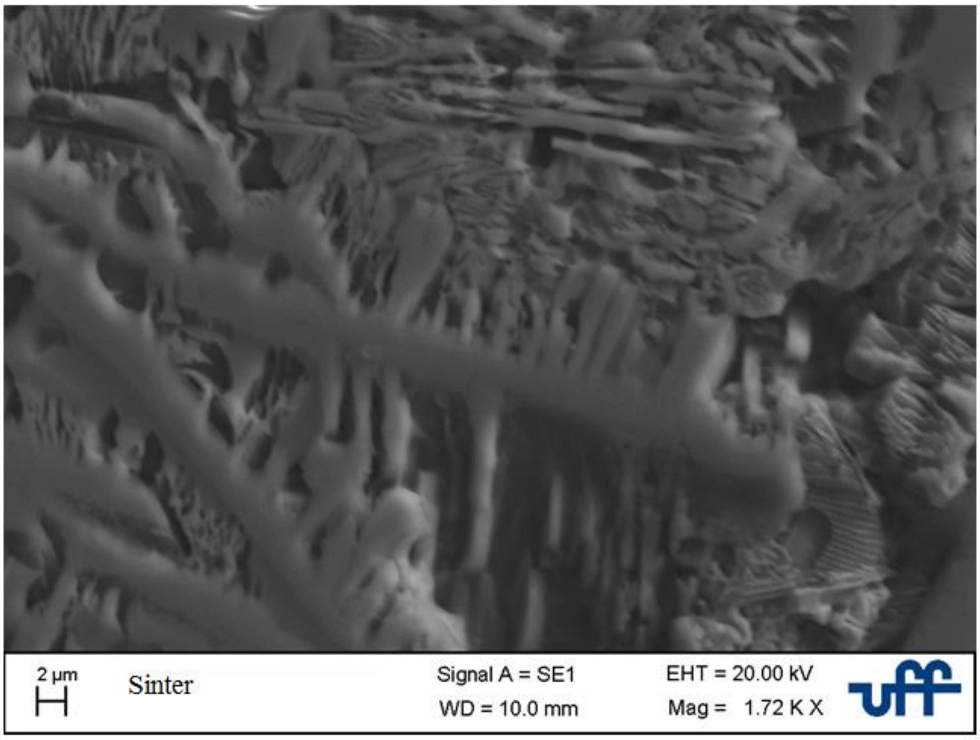
$$\frac{\partial(\rho_i\varepsilon_i u_{i,j})}{\partial t}+\frac{\partial(\rho_i\varepsilon_i u_{i,k}u_{i,j})}{\partial x_k}=\frac{\partial}{\partial x_k}\left(\mu_i\frac{\partial u_{i,j}}{\partial x_k}\right)-\frac{\partial P_i}{\partial x_j}-F_j^{i-l} \tag{1}$$

Continuity:

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



a) Sinter bed control volume – physical domain



b) Typical sinter microstructure

Figure 2 Sinter bed for domain calculation and expected final microstructure of the sinter product

Enthalpy balance:

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

Chemical species

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

In the Eqs. (1)-(4) the indexes i and l represent the phases, j and k are the indexes 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 phase 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-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-l}, given in Eq. (5).

The set of differential equations, Eqs. (1)-(4), are solved using the boundary conditions that represents the process of gas suction and solid feeding as well as the heat losses by the environment by convections and radiation. The numerical solution is obtained by using the finite volume method based on the power law scheme to compute the algebraic coefficients and the algorithm SIMPLE (Semi Implicit Method for Pressure Linked Equations) is applied to solve the velocity components and pressure simultaneously (Melaen, 1992).

$$F_g^s=\left[1.75\rho_g+\frac{150\mu_g}{\left|\vec{U}_g-\vec{U}_s\right|}\left(\frac{\varepsilon_s}{d_s\varphi_s}\right)\right]\left(\frac{\varepsilon_s}{(1-\varepsilon_s)^3 d_s\varphi_s}\right)\left|\vec{U}_g-\vec{U}_s\right|\left(u_{g,j}-u_{s,j}\right) \tag{5}$$

$$E^{g-s}=\frac{6\varepsilon_s}{d_s\varphi_s}\frac{k_g}{(d_s\varphi_s)}\left[2+0.39\left(\frac{\rho\left|\vec{U}_g\right|}{\mu_g}(d_s\varphi_s)\right)^{1/2}\left(\frac{\mu_g C_{p,g}}{k_g}\right)^{1/3}\right]\left(T_g-T_s\right) \tag{6}$$

$$\varepsilon_i=1-\left(0.403[100d_i]^{0.14}\right)\left(1-MAX\left(0,\ MIN\left(1,\ \left(\frac{T_s-T_{im}}{\Delta T_m}\right)\right)\right)\frac{S_m}{100}\right) \tag{7}$$

$$\varepsilon_s=\sum\varepsilon_i+\varepsilon_l+\varepsilon_{ls}\quad \text{and}\quad \varepsilon_g=1-\varepsilon_s \tag{8}$$

Where ε stands for the individual solid and gas volume fractions, k is the thermal conductivity d_i is the single particle diameter and Sm is the shrinkage melting down factor and Tm is the initial softening and melting temperature. These parameters are obtained using standard softening and melting experiment for the raw materials (Nogueira & Fruehan, 2006).

3. RESULTS AND DISCUSSIONS

This section presents and discuss the model results. Firstly, a model verification is presented for the traditional sinter machine operation based on fossil fuel and afterwards the model is used to predict novel operation techniques for 100% of biomass fuel and oxygen injection in the furnace zone. Figure 3 shows the temperature distribution for vertical central plane and the positioning of thermocouples used to monitoring the inner bed conditions. As can be observed, the temperature distribution presents a narrow combustion and sintering zone and clearly is observed a deficit of energy at the top surface of the bed, indicating that this region the residence time is shorter and hence inhomogeneous sinter product. Figure 4 shows the temperatures measured and calculated for 3 levels of the bed. A quite good agreement of the measured and calculated results is obtained.

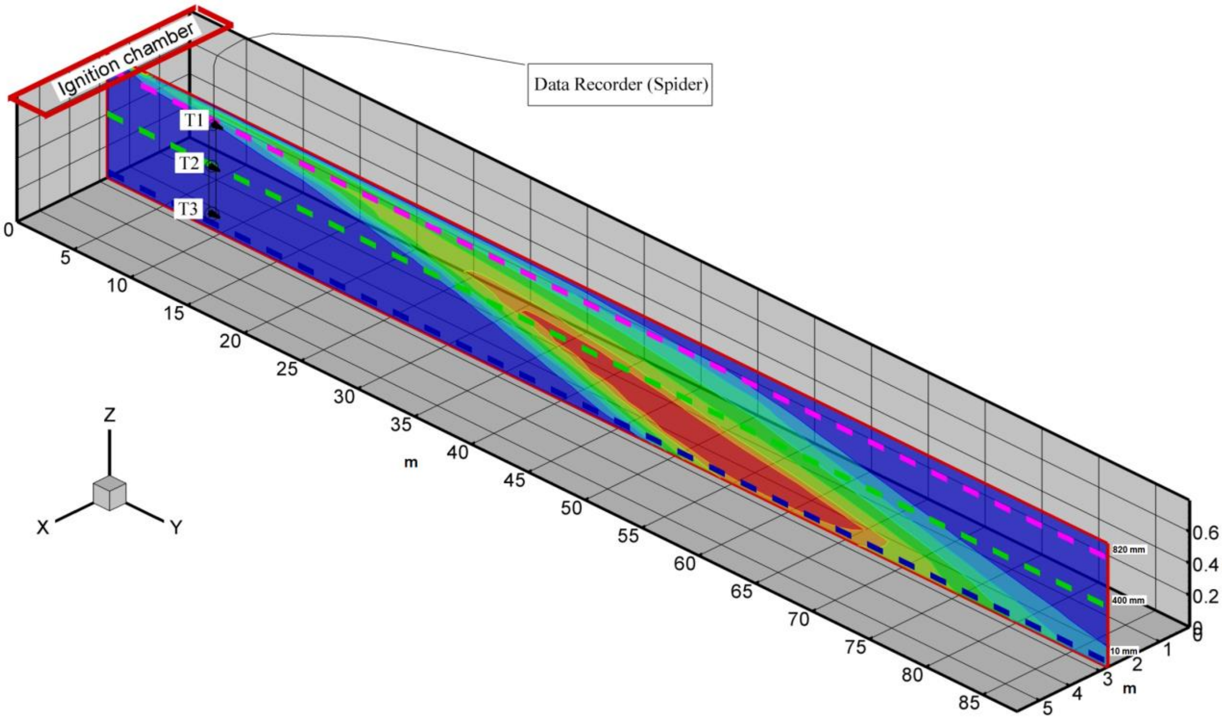


Figure 3 Thermocouples positioning inside the sínter bed for model verification

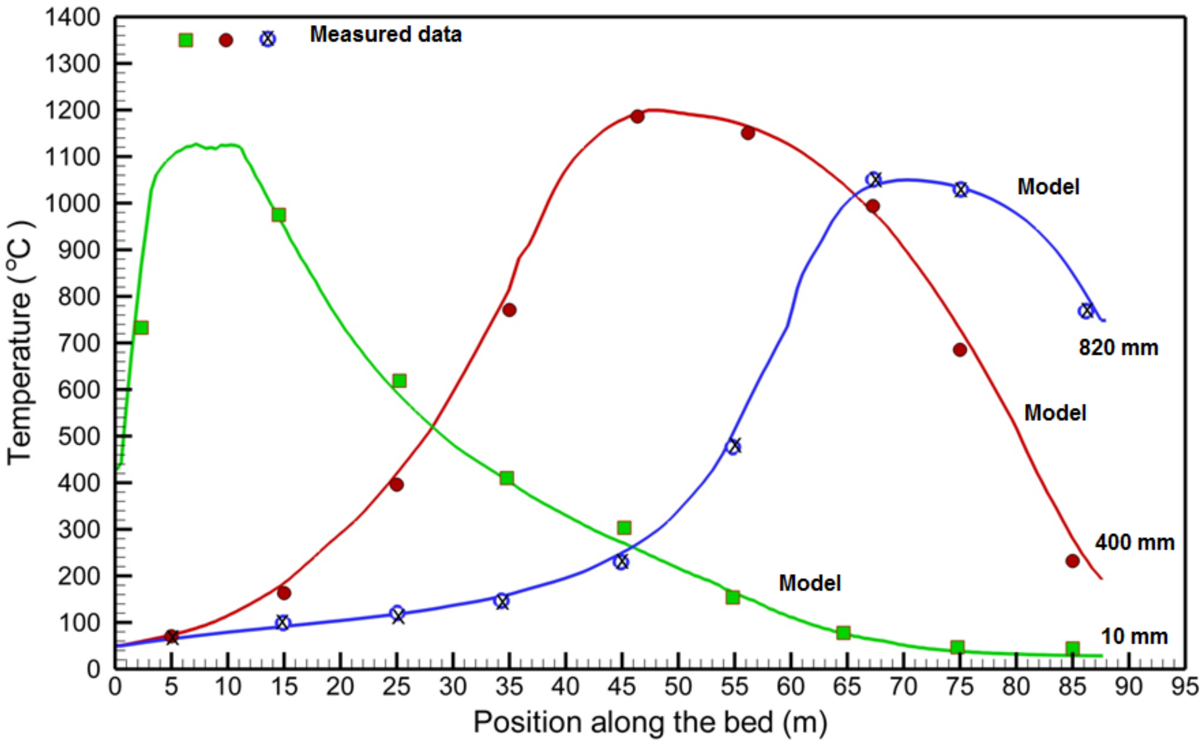


Figure 4 Model predictions of bed temperatures and comparison with industrial measured data

Figure 5 shows the temperature distributions for a base case of 100% of biomass used as fuel in a compact sinter machine. Observing the sintering zone is possible to affirm that the process is working similarly to the conventional operation but in a shorter machine but still the top region is narrower than the central region, which leads to non-uniform sintering. Figure 6 shows the case1 where oxygen is injected until the 10th wind box and comparing with Fig. 5 the sintering zone was enlarged at the top of the sinter bed, but as the suction flow rate was kept constant, decrease in the extension of the sintering zone is observed.

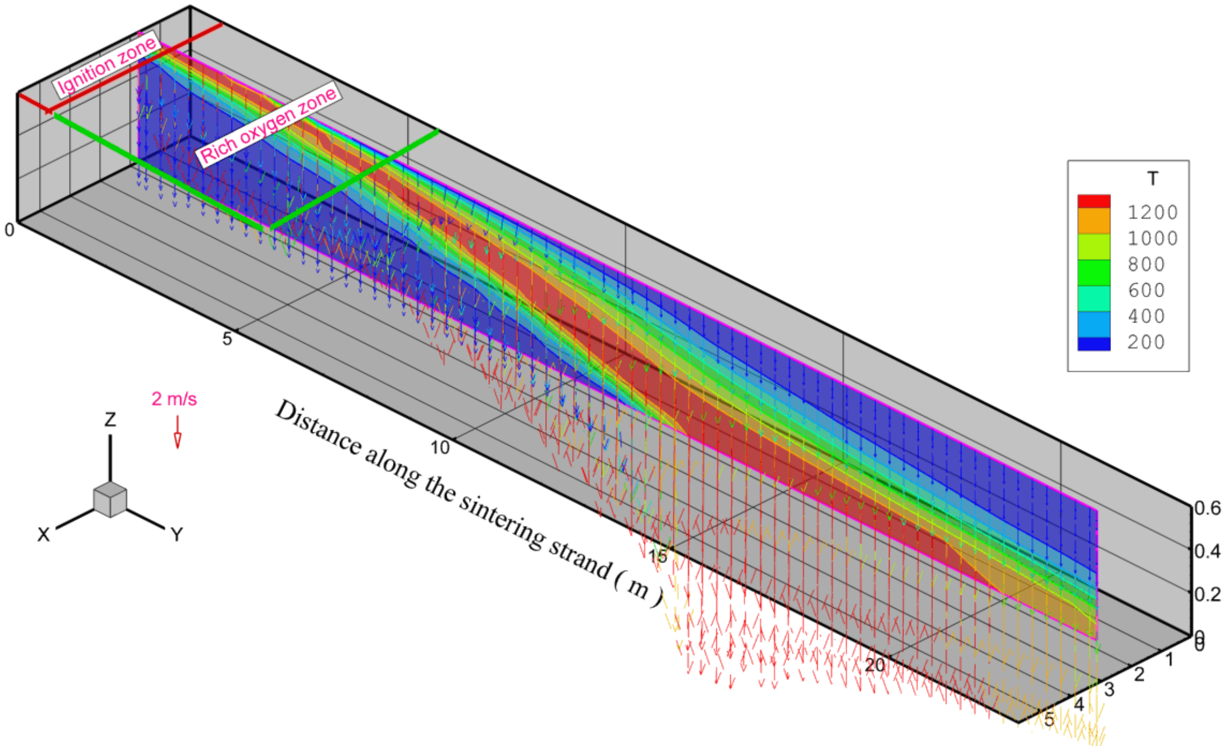


Figure 5 Base case of industrial operation of a small sintering machine based on biomass fuel

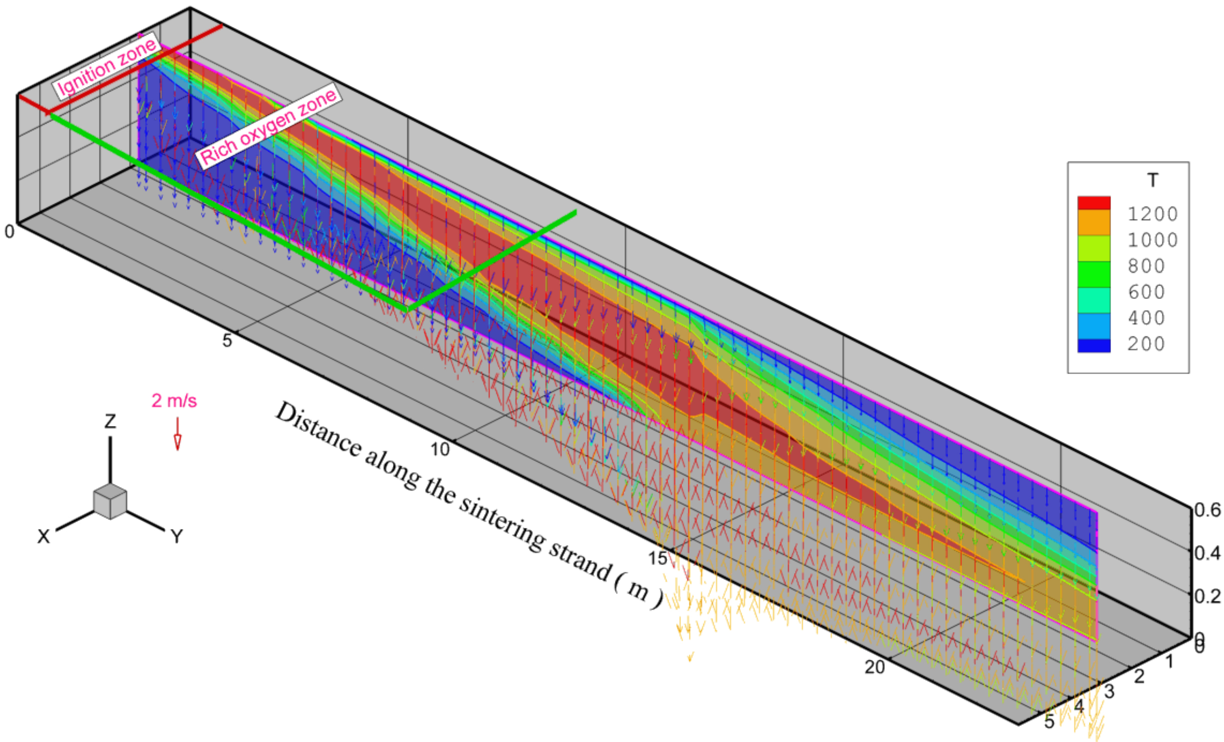


Figure 6 Model predictions for biomass operation with oxygen injection – case 1

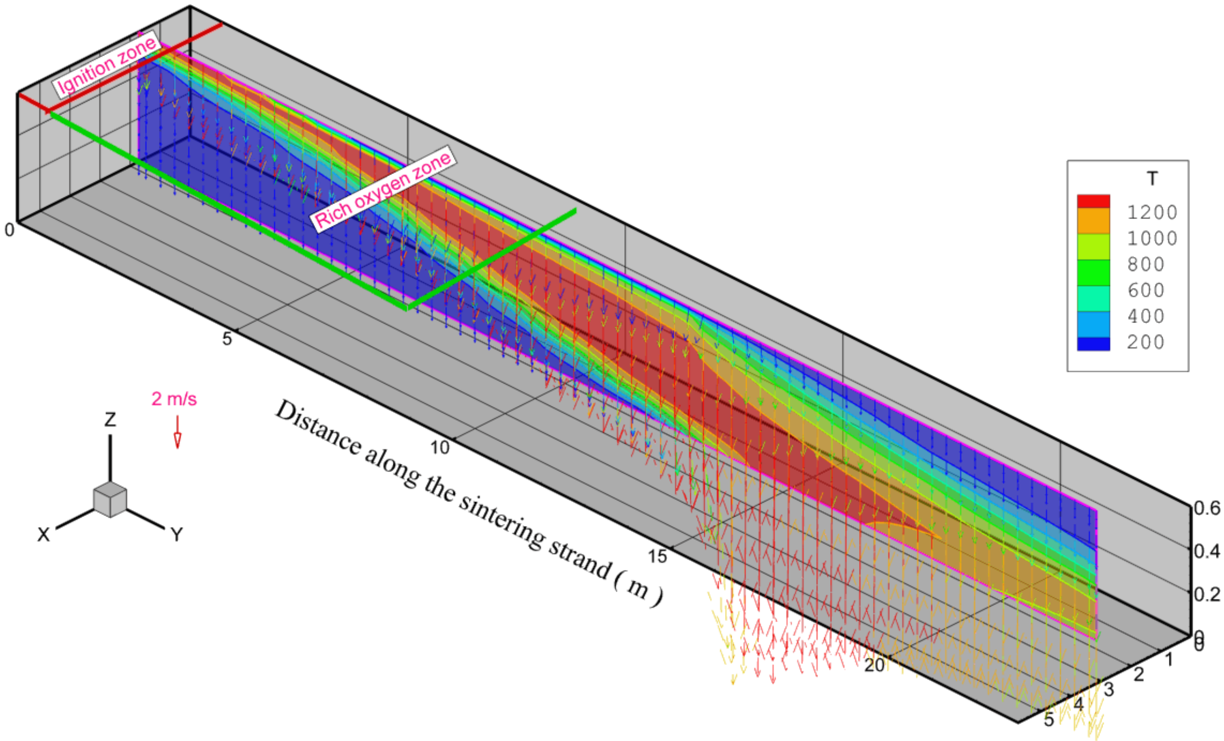


Figure 7 Model predictions for biomass operation with oxygen injection –case 2

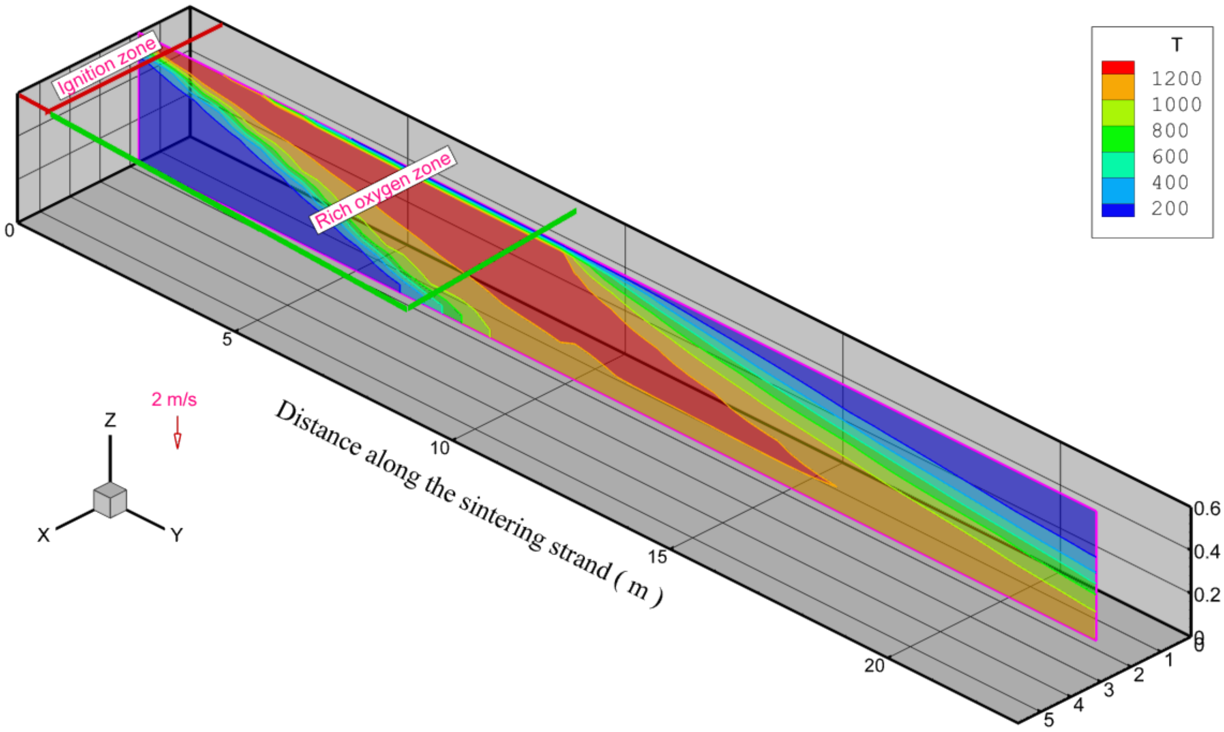


Figure 8 Model predictions for biomass operation with oxygen injection –case 3

Figures 7 and 8 show the temperature distributions for case 2 and 3 and 3, respectively. As can be seen, the in Fig. 7 an uniform sintering zone is obtained, indicating that this case would be suitable for sintering operation. These features was confirmed by the amount of return sinter (20% less) and higher average sinter size (about 15%). The calculation results shows that the combination of uniform suction with oxygen replacement in the 10 first wind boxes promotes larger sintering front and hence expected better sintering properties. As the biomass reactivity is higher than coke breeze, the speed of the sinter strand was increased 25% when compared with the conventional operation. The fuel rate for the best-case simulated (case 2) increased due to lower calorific value of the biomass.

4. CONCLUSIONS

In this paper, by using a comprehensive mathematical model, the compact iron ore sintering machine design is proposed based on biomass and oxygen injection. Simulation results indicated that feasible operation conditions could be obtained using 100% of biomass fuel in a shorter machine with faster strand velocity due to higher combustibility of the biomass.

5. ACKNOWLEDGEMENTS

Faperj, CNPq, CAPES and FINEP supported this work. The authors thank CSN and VALE

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