Original Article

Analyzing technological alternatives of solid and gaseous fuels for iron ore compact sintering machines applying a multiphase mathematical modeling

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Abstract

The steel industry has faced challenges regarding the raw materials and fuels, and hence economic and environmental restrictions. This paper is focused on searching alternatives based on biomass and gaseous fuels suitable for replacing the coke breeze fossil fuel. The iron ore sintering process is a key technology in the steel industry due to its possibility of recycling waste solids or powders internally produced during the raw materials handling or subsequent process of steel production. However, this process is also recognized as one of the most critical units with regard to particulates and polychlorinated dioxins and furans (PCDD/F, NOx, SOx) emissions. The outlet gas treatment involves the cleaning with electrostatic precipitator and filter bags. New process concepts and technologies have been proposed such as gas recycling, fuel gas injection and biomasses fuels besides recycling waste solids replacing natural raw materials. Nevertheless, testing these technologies is expensive. Therefore, comprehensive mathematical models based on transport phenomena are efficient tools to study and indicate new possibilities for designing operational conditions as well as resizing the machines for minimizing the hazardous emissions. In this study, the model principles and analysis cases are presented and discussed. A technological proposal for using waste solid biomass in the iron ore sintering process is analyzed using the specific hazardous emissions of PCDD/F, NOx, SOx and particulates as decision parameter. It was also evaluated proposals for the use of process gases and hydrogen fuel as partial substitution to coke breeze. The results indicated that about 20% of the solid fossil fuels could be replaced by waste solid residue of biomass (processed as small pellets) generated during the charcoal production and handling and wood processing, or by injection of fuel gases such as coke oven gas, BF gas and hydrogen, resulting in benefits such as productivity gains, lower carbon intensity and reduced PCDD/F, NOx, SOx emissions.

Keywords: Modeling; Cleaner sintering process; Solid wastes; Biomass; Hydrogen.

1 Introduction

The steel industry is widely recognized as a significant contributor to carbon emissions and a substantial consumer of fossil energy. In the stages involving the preparation of raw materials, approximately 50 kilograms of fossil coal are utilized per ton of product [1,2]. Consequently, there is a growing need for innovative technologies that aim to mitigate carbon emissions. Among these operational units within the integrated steel industry, the iron ore sintering process holds particular importance. It plays a vital role in the steelmaking industry by providing the necessary raw materials for the blast furnace and facilitating the internal recycling of fines generated throughout the melt shop. The size and capacity of sintering machines vary, primarily dictated by the design and capability of their air suction systems. Nevertheless, larger machines, while generally achieving high energy efficiencies, struggle to handle low-grade raw materials effectively. As a result, compact and smaller machines are gaining popularity due to their versatility in utilizing various raw material sources and lower-grade iron ores [1,2].

The traditional sintering plant comprises several components, including a raw material preparation station, a blowing and suction system, a sintering conveyor, a gas cleaning unit, a cooling system, and a sintered product classification complex. Figure 1 illustrates a schematic representation of the sinter plant along with the auxiliary systems mentioned. Depending on the desired composition of the final product, raw materials received by the dosing system are directed to a bed and then to a mixer and micropelletizer, where binders and additives are adjusted accordingly. This process results in the mixing of materials,

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generating fine particles, and larger particles and micropellets are subsequently conveyed onto the moving sintering belt, where the sintering process occurs. After completing this process and passing through the sintering belt, the materials are discharged in the cooling plant and sorted into different categories. The fines are reintroduced into the process to serve as nucleating particles and for bed protection.

The gas generated during the sintering process undergoes purification and is subjected to a cleaning system featuring electrostatic precipitators and filters before being released into the environment. Recent efforts have explored the possibility of recycling this gas, which is considered in this work as a subject of analysis. Another potential approach is to partially replace solid fuels with steelmaking gases like blast furnace and coke oven gases. This article also investigates case studies where such technology is taken into account. Furthermore, the option of replacing solid fuels with small biomass pellets derived from charcoal fines and wood processing is considered. Lastly, this work examines cases that assess the effects and prospects of utilizing hydrogen in the sintering process.

In this study, the ignition furnace undergoes modification and enlargement, with the division of the gas burnout zones. This adjustment enables the utilization of gas fuel and the injection of oxygen into five wind boxes, with the aim of enhancing the efficiency of the sinter machine and reducing specific emissions. The burner furnace is adapted to feature two zones: an ignition zone utilizing natural gas, and a gas burner zone employing steelmaking or biogas with oxygen enrichment.

This concept is well-suited for designing various gas utilization systems. The feeding system has been adjusted to include height control and facilitate uniform bed adjustments.

Numerous efforts have been dedicated to developing innovative technologies to address environmental concerns and lower the carbon emission intensity associated with steelmaking [3-6]. The steelmaking process is intricate, involving various physical and chemical phenomena such as heat transfer, mass transfer, and momentum transfer, all interwoven with chemical reactions [7-11]. These phenomena occur concurrently, significantly increasing the complexity of process analysis. Consequently, an effective approach to devising new concepts and quantifying their impact is to create phenomenological mathematical models that can simultaneously account for mass transfer through reliable rate equations for chemical reactions, momentum transfer within a complex bed structure, and interphase heat transfer, which considers convection, radiation, and heat generation from chemical reactions [3-5,7-17].

The primary aim of this research is to propose enhancements for the sintering machine, intending to boost process flexibility and enable operational practices such as gas reuse, the use of fuel gases (including hydrogen), and partial incorporation of biomass through micropellet agglomeration with traditional fossil fuels like coke breeze or anthracite. These applications have significant implications for the environmental performance of iron ore sintering, which is of critical importance for the efficient operation of an integrated steel plant, giving relevant insights into the potential for mitigation of GGEs, and thereby promoting cleaner production practices.

2 Methods

To explore various technological alternatives, the study examined four distinct analysis cases dealing with coke breeze substitution by solid or gaseous fuels, such as coke oven gas (COG) and blast furnace gas (BFG), biogas from biomass gasification, biomass micropellets and, finally, hydrogen fuel gas.

The criterion adopted for this substitution was keeping the temperature close to that of sintering in the upper layers while allowing enough residence time for SFCA formation. Although these fuels exhibit considerably lower calorific values in comparison to coke breeze, the substitution rate was defined taking this data into account. Basicity for each analyzed case was kept around 1.8 since optimal sinter quality is found when basicity ranges from 1.5 to 2.0 [11].

2.1 Model development

The iron ore sintering process occurs on a moving belt, where air is drawn into the bed horizontally as it advances. Inside the bed, a complex interplay of phenomena takes place, involving various chemical reactions. To effectively model the inner workings of the bed, a mathematical model is introduced in this study. This model is built upon a system of partial differential equations that capture the conservation principles for momentum, energy, and chemical species in the gaseous, solid (comprising raw material and solidified liquid), and molten phases. It aims to simulate the characteristics of the inner bed.

The model's scope is limited to the control volume of the bed, where gas flows horizontally through it. These differential equations, denoted as Equations 1-4, are solved using boundary conditions that mirror the processes of gas suction and solid material input. Additionally, they account for heat losses to the environment through convection and radiation processes.

Furthermore, the model incorporates additional relationships that describe the transfer of momentum and energy between different phases, as outlined in Equations 5 and 6. Equations 7 and 8 represent the influence of the softening and melting properties of the raw materials, which have a substantial impact on bed permeability, as well as heat and mass transfer.

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

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

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

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

$$F_j^{g-s}=\left[1{,}75\rho_g+\frac{150\mu_g}{\left|u_{g,j}-u_{s,j}\right|}\left(\frac{\varepsilon_s}{d_s\varphi_s}\right)\right] \left(\frac{\varepsilon_s}{\left(1-\varepsilon_s\right)^3 d_s\varphi_s}\right)\left|u_{g,j}-u_{s,j}\right|\left(u_{g,j}-u_{s,j}\right) \tag{5}$$

$$E^{g-s}=\frac{6\varepsilon_s}{d_s\varphi_s}\frac{k_g}{d_s\varphi_s}\left[\frac{2+0{,}39\left(\frac{\rho\left|U\right|}{\mu_g}\left(d_s\varphi_s\right)\right)^{\frac{1}{2}}}{\left(\frac{\mu_g C_{p,g}}{k_g}\right)^{\frac{1}{3}}}\right]\left(T_g-T_s\right) \tag{6}$$

$$\varepsilon_s=1-(0{,}403[100d_s]^{0{,}14} \left(1-MAX\left(0,MIN\left(1,\left(\frac{T_s-T_m}{\Delta T_m}\right)\right)\right)\frac{S_m}{100}\right) \tag{7}$$

$$\varepsilon_g= \ -\varepsilon_s \tag{8}$$

The thermophysical properties of each phase, including thermal conductivity (k), thermal capacity (Cp), viscosity (μ), and specific mass (ρ), are contingent upon both composition and temperature. Meanwhile, the symbols ε_g and ε_s denote the volume fractions of the individual solid and gaseous phases, with d_s representing the diameter of a single particle. S_m accounts for the melting and contraction factor, and T_m is the initial softening and melting temperature.

To determine these parameters, standard softening and melting experiments for the considered raw materials have been conducted [12,13,16].

The chemical reactions that occur within the sinter bed primarily involve gas-solid reactions. Processes like water vaporization, partial softening, melting, and solidification are presumed to be influenced by the rates of heat supply and cooling. On the other hand, combustion, reduction, and oxidation are believed to be dependent on temperature and gas composition.

Rate equations governing these mechanisms can be derived from prior research and publications. The impact of raw material compositions is factored into these rate equations using phenomenological models and empirical data [1-5,18-20]. Notably, in this study, new raw materials are introduced into the model. These materials, specifically solid fuel micropellets produced from fine residues of biomass and wood, are incorporated by considering parameters such as ignition temperature, combustion heat, and apparent activation energy, which are determined through thermogravimetric experiments and differential scanning calorimetry [20].

2.2 Numerical characteristics of the model

The numerical solution is achieved through the finite volume method, which enables the integration of the differential equations into a system of discretized algebraic equations. Coefficients are determined using the power-law scheme. The momentum and continuity equations for each phase are concurrently solved using the SIMPLE algorithm (Semi Implicit Method for Pressure Linked Equations). This algorithm facilitates the simultaneous calculation of velocity and pressure components within a non-uniform staggered grid [21,22].

To ensure accuracy, the discretization of the bed domain was continuously refined until an average error of less than 1% was attained for the momentum and energy equations. This refinement led to a final number of control volumes, which amounted to 22x165x16 for the cases analyzed in this study.

The solution to the set of coupled nonlinear algebraic equations is determined interactively through a TDMA-based line-by-line iteration procedure [21,22]. Convergence is achieved when a maximum error value of 10^{-3} is met for all variables estimated within the control volumes, thereby ensuring a high level of numerical precision.

The calculation time is machine-dependent. This model is suitable for execution on personal computers and can also be adapted for parallelized versions optimized for multicore machines.

3 Results and discussion

3.1 Model validation and verification for reference operation

The model's validity was established through prior verification conducted on the compact sintering machine. This verification process involved the utilization of industrial data, which was gathered by placing thermocouples throughout the entire length of the sintering bed. Additionally, temperature data was acquired from the wind box during the verification process.

Both the calculated and measured results were compared, and they exhibited strong agreement, as demonstrated in Figures 2 and 3. These comparisons were made within the

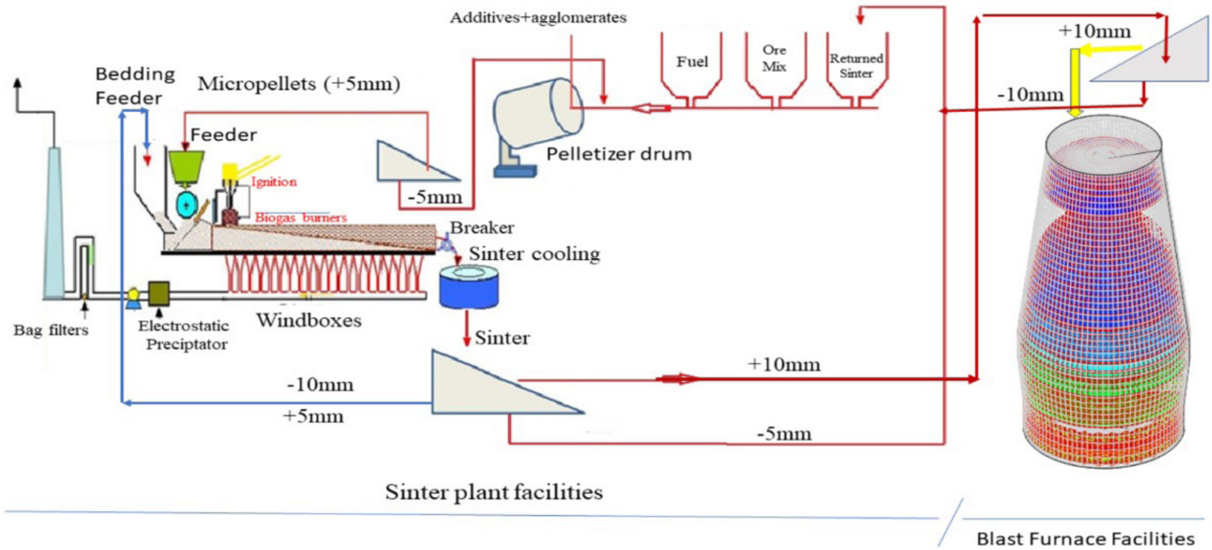

Figure 1. Flowchart illustrating a compact iron ore sintering facility that offers the option of utilizing solid waste-based fuels.

interior of the compact machine's bed, specifically during its operation with conventional fuel (coke breeze), as depicted in Figure 2. Throughout the process, wind boxes temperatures were recorded along the conveyor and compared to the model's calculated steady-state conditions. Consequently, it is evident that the model closely approximated the average gas output temperatures in each wind box, as depicted in Figure 3. This level of agreement indicated the model's accuracy, thus enabling its application to assess various operational conditions in the subsequent case analyses.

To explore these technologies, four distinct analysis cases were considered. The first case explores the potential for partially replacing coke breeze with a mixture of coke oven and blast furnace gas. The second case investigates substitutions with biogas generated through biomass gasification. In the third case, coke breeze is replaced by solid fuel consisting of biomass micropellets produced from coal fines and wood processing dust. Lastly, the fourth case introduces partial substitution with a blend of preheated air and fuel hydrogen. It's worth noting that these alternative fuels possess lower calorific values and exhibit faster reaction rates. Consequently, a substitution rate was calculated by comparing the heat released for each fuel to that of coke breeze.

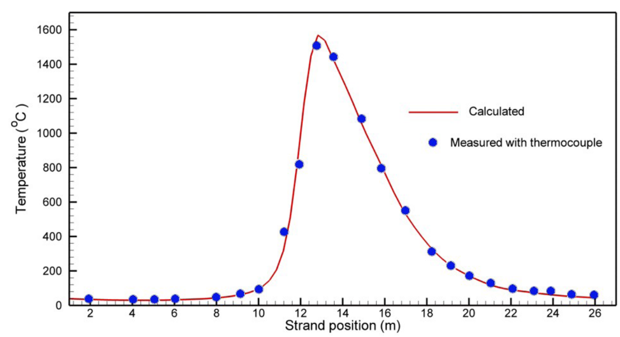

Figure 2. Predictions made by the model and actual measurements of the internal bed temperature in a compact sintering machine during standard operation.

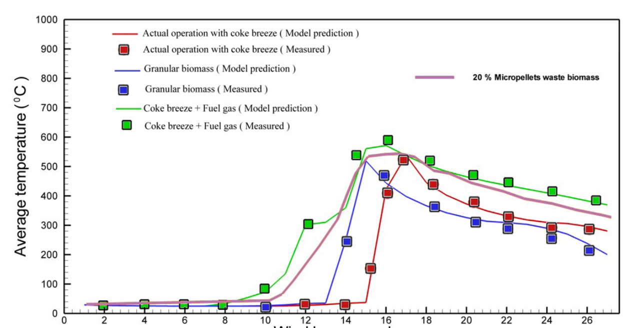

Figure 3. Confirmation of the overarching model's accuracy through a comparison of the average temperatures exiting the wind boxes with the predictions generated by the model for the various analysis cases.

3.2 Analysis of emission reduction cases

3.2.1 Solid fuel substitution by coke oven and blast furnace gas

As depicted in Figure 4, the temperature distribution pattern within the sintering bed illustrates the scenario where fuel gas is injected into the sintering machine while steelmaking gas is employed in the preheating zone. This approach becomes feasible when the steel plant has an excess supply of gas available from its coke oven facilities. Within the combustion zone, the temperature distribution maintains stable conditions, with maximum temperatures well-suited for the predominant mechanism of liquid formation and solidification. This characteristic results in the production of high-quality sinter, comparable to what is achieved when using coke breeze as fuel.

The adoption of this approach also leads to a significant reduction in specific emissions of SOx, NOx, and PCDD/F. This decline can be attributed to alterations in the raw materials used and modifications in the conditions within the strand, which effectively suppress the formation of these hazardous compounds.

3.2.2 Solid fuel substitution by biogas (gasification of biomass)

When considering the substitution of coke breeze by the use of biogas, the model prediction indicated that a larger high temperature zone is obtained by the combination of the equivalent heat substitution rate with faster reactions within the combustion front supported by the additional oxygen. Thus, it is clearly demonstrated that this condition is favorable for the liquid phase formation mechanism during sintering, which should produce greater mechanical strength and lower sinter return.

The temperature profiles depicted in Figures 4 and 5 were achieved through an interactive adjustment of strand velocity to reach the burnout temperature point. Throughout these calculations, the bed height remained constant. Consequently, the temperature distribution reflects the reactivity of the fuel and the injection points.

In the case of Figure 5, as compared to Figure 4, the mixed gas possesses a lower calorific value, and the injection of oxygen takes on a primary role in distributing heat at the sintering front. Notably, biogas in Figure 5 contains a significant amount of H_2 and CO compared to the mixed gas in Figure 4.

Despite the increased total fuel quantity in this scenario, several clear advantages emerge. The reactivity of the fuel gas is higher, and the heat supply is more evenly distributed, allowing the sinter strand to achieve higher velocity while maintaining a similar temperature distribution profile. Another highly desirable aspect is that all the replacement and additional fuel sources are renewable. Therefore, this option combines the substitution of fossil fuel with biogas, thereby enhancing machine productivity and ensuring process feasibility and economic viability.

3.2.3 Solid fuel substitution by biomass waste micropellets

To effectively address this scenario, adjustments were made to the strand velocity to maintain the burnout temperature at 900 ºC. This strategic approach led to a notable increase in productivity, approximately 15%, while also resulting in a minor reduction in the apparent density of the bed materials.

Figure 6 shows that when partial replacement of coke by micropellets produced from biomass residues is carried out, the temperature pattern shows an uniform thickness for the sintering zone, which indicates that a uniform quality of the final product is expected and, therefore, lower return of fine materials. Therefore, this operational technique is demonstrated to be viable.

3.2.4 Solid fuel substitution by hydrogen

For this case, three different subcases were investigated, as well as their impact on the formation of the

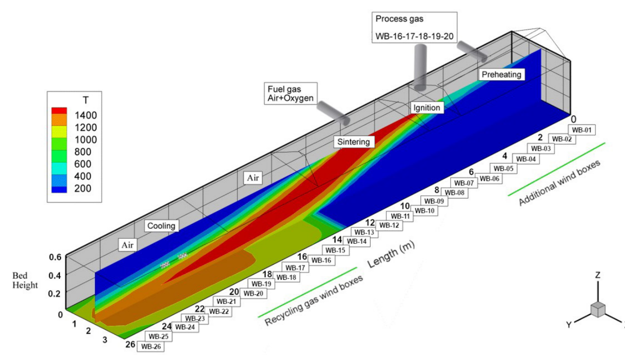

Figure 5. Temperature pattern observed in the scenario where biogas generated from the gasification of biomass is used to replace solid fuel (coke breeze) at a replacement ratio of 1.6 kg of biogas/ 1 kg of coke breeze.

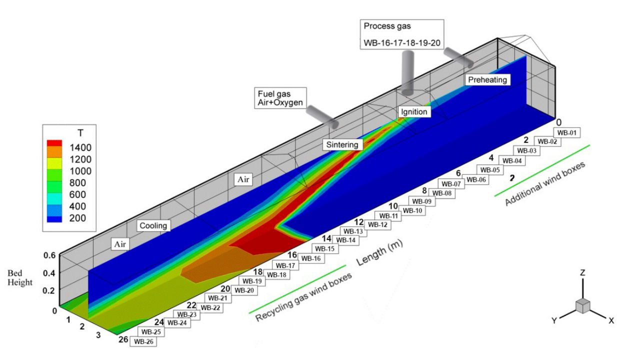

Figure 4. Temperature pattern observed in the scenario where a mixture of 20% coke oven gas and 80% blast furnace gas is employed to substitute solid fuel (coke breeze) at a replacement ratio of 1.5 kg/1 kg of coke breeze.

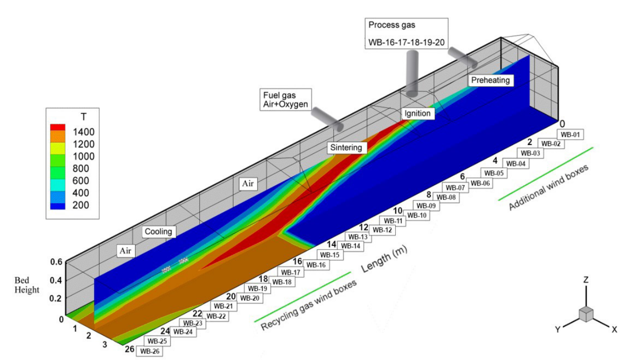

Figure 6. Temperature pattern observed in the scenario where micropellets derived from biomass residues are used to replace 20% of the solid fuel (coke breeze) at a replacement ratio of 2 kg of micropellets/1 kg of coke breeze.

SFCA phases (SFCA and SFCA-I or SFCA I and SFCA II, depending on the nomenclature adopted). These subcases consist of different levels of injection of preheated air and hydrogen fuel, with subcase #1 addressing the effects of injecting preheated air into the preheating zone along with a mixture of preheated air and hydrogen into the sintering zone, subcase #2 considers, in addition to the parameters adopted for subcase #1, the injection of preheated air into the ignition zone, while subcase #3 evaluates the injection of the mixture of preheated air and hydrogen into the ignition and sintering zones while maintaining the injection of preheated air into the preheating zone. The results can be seen in Figures 7, 8 and 9, respectively, for subcases 1, 2 and 3.

Figure 10 shows the temperature profile obtained for each subcase analyzed. It shows the interval for calcium-ferrites (SFCA) formation, which are beneficial for the general quality of the sinter formed during the process. It is observed that subcase #2 presents the longest time interval maintained at the temperature necessary for the precipitation of such phases, followed by subcase #3 and, finally, subcase #1.

The findings of this study demonstrate the feasibility of the evaluated scenarios, showcasing their potential to partially substitute coke breeze.

Additionally, productivity gains are achievable due to the accelerated combustion of utilized gases and biomasses. Model predictions suggest a productivity increase ranging from 5% to 25% by adjusting the biomass to coke breeze ratio up to 20%, coupled with corresponding modifications in strand velocity, oxygen levels, and replacement ratios. Consequently, the proposed new technologies for the compact sinter machine hold significant promise for fostering a cleaner and more sustainable steel industry.

Notably, the specific carbon intensity of the process can be significantly reduced through the utilization of micropellets derived from biomass fines. SOx emissions experience a marked decrease compared to the base case of using only coke breeze, attributed to the low sulfur content of biomass and biogas, as well as reduced particulate matter when employing biomass pellets. These outcomes stem from the total combustion of fuel and the limited presence of ultrafines in the sintering mixture, facilitated by the intensive use of the micropellet system and incorporation of fine sinter as nucleation materials.

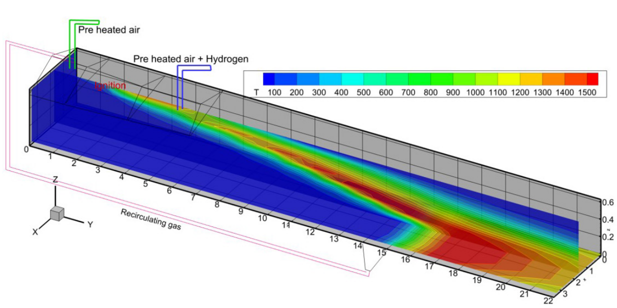

Figure 7. Temperature pattern for subcase #1 of partial replacement of solid fuel (coke breeze) by hydrogen.

Relative to the coke breeze practice, the carbon intensity parameter decreases by approximately 25% in the best-case scenario of 20% coke breeze replacement with biomass pellets.

Results obtained for the hydrogen fuel injection cases exhibited enhanced SFCA formation as well as overall improved productivity, yielding a better sinter quality in shorter times.

Mass balance analysis of SOx, NOx, and PCDD/F emissions underscores the advantageous nature of the proposed scenarios, indicating significant reductions in these compounds. A similar trend is observed for particulate emissions, attributed to improved control of in-bed gas flow conditions achieved by charging biomass as pellets and minimizing ultrafine particles through the micropelletizer system.

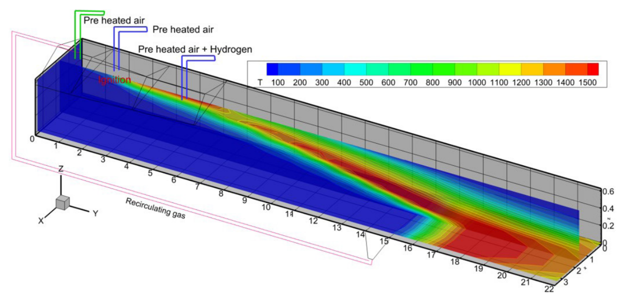

Figure 8. Temperature pattern for subcase #2 of partial replacement of solid fuel (coke breeze) by hydrogen.

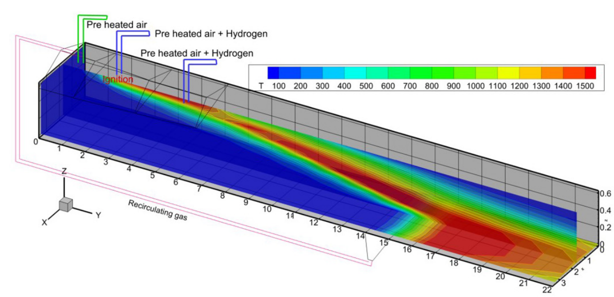

Figure 9. Temperature pattern for subcase #3 of partial replacement of solid fuel (coke breeze) by hydrogen

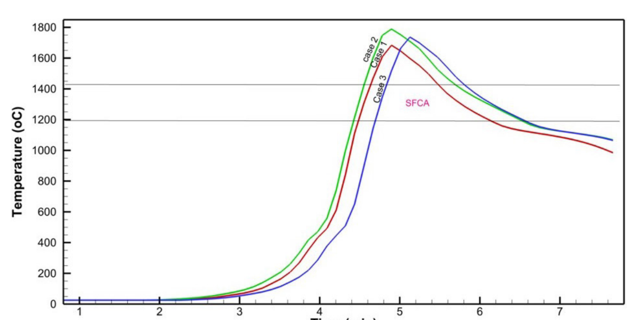

Figure 10. Temperature profile as a function of time of the different subcases analyzed considering the extension of the formation interval of the SFCA phases that provide an increase in sinter quality.

4 Conclusion

This article explores alternative energy sources for sintering plants within integrated steel mills, diverging from the conventional use of fossil fuels. The compact sintering machine demonstrated versatility by embracing various fuels such as micropellets, gas injections such as biogas and hydrogen, as well as oxygen enrichment. A comprehensive mathematical model was employed to analyze these alternatives, enabling simulations of a fuel-flexible compact sintering machine. Subsequently, the model facilitated investigations into feasible operations leveraging steelmaking gases, biogas, hydrogen, and micropellets derived from fine solid waste fuels. Simulation outcomes underscored the feasibility of operational conditions achieved through the partial substitution of coke breeze with steelmaking gases and biogas in a more compact machine, benefiting from accelerated conveyor speeds attributed to heightened combustion rates of these alternative fuels. Oxygen enrichment practices were harnessed to intensify frontal combustion and sustain flame stability, thereby ensuring adaptability to various fuel types. The model forecasts indicate that the replacement of coke breeze by biomass up to 20% could lead to a productivity increase ranging from 5% to 25%, while SOx, NOx, and PCDD/F are considerably reduced. Additionally, analyses of scenarios incorporating hydrogen fuel exhibited favorable outcomes, notably enhancing the formation of calcium ferrites and overall process productivity, thereby bolstering sinter quality.

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