Original Article

A theoretical study using the multiphase numerical simulation technique for effective use of H₂ as blast furnaces fuel

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A B S T R A C T

We present a numerical simulation procedure for analyzing hydrogen, oxygen and carbon dioxide gases injections mixed with pulverized coals within the tuyeres of blast furnaces. Effective use of H₂ rich gas is highly attractive into the steelmaking blast furnace, considering the possibility of increasing the productivity and decreasing the specific emissions of carbon dioxide becoming the process less intensive in carbon utilization. However, the mixed gas and coal injection is a complex technology since significant changes on the inner temperature and gas flow patterns are expected, beyond to their effects on the chemical reactions and heat exchanges. Focusing on the evaluation of inner furnace status under such complex operation a comprehensive mathematical model has been developed using the multi interaction multiple phase theory. The BF, considered as a multiphase reactor, treats the lump solids (sinter, small coke, pellets, granular coke and iron ores), gas, liquids metal and slag and pulverized coal phases. The governing conservation equations are formulated for momentum, mass, chemical species and energy and simultaneously discretized using the numerical method of finite volumes. We verified the model with a reference operational condition using pulverized coal of 215 kg per ton of hot metal (kg th⁻¹). Thus, combined injections of varying concentrations of gaseous fuels with H₂, O₂ and CO₂ are simulated with 220kg th⁻¹ and 250kg th⁻¹ coals injection. Theoretical analysis showed that stable operations conditions could be achieved with productivity increase of 60%. Finally, we demonstrated that the net carbon utilization per ton of hot metal decreased 12%.

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1. Introduction

The hot metal elaboration unit operation during the primary metallurgy of the iron production is the most intensive in carbon, where the route blast furnace (BF) – basic oxygen furnace (BOF) is predominant due to economical and production scale reasons. Nevertheless, this production route is intensive in energy and demands specific and elaborated quality for the raw materials as coke and granular sinter, which allows higher efficiency of the reduction step with excellent gas utilization ratio. Conversely, the production of rich hydrogen gas from coal gasification process using fossil or renewable resources has become economically viable using newly developed technologies. Therefore, new efficient use of rich hydrogen gas in this industry is a promising issue to be addressed [1,2]. In the primary steel integrated production route, the BF operation unit is responsible for nearly 70% of the demanded energy. The fuel and reducing agent consumptions represent more than 60% of the total cost of pig iron production in this processing route. These materials are consumed in the blast furnace as granular coke or pulverized coal (PC) fed through the tuyeres of the reactor. Consequently, efforts have been addressed to decrease the reducing agent rate (RAR), or at least, to replace the coke consumption of the process by alternative materials injected through the blast furnace tuyere, which makes the process less carbon intensive and environment friendly [3–10]. The desired increase on the pulverized coal injection is a complex and challenging task for the blast furnace technology. The reasons are mainly due to the gas flow control and unburned coal particles accumulation in the lower part of the furnace, which can generate unstable solid and liquids descending motions [8–10]. To analyze the complexes phenomena that take place in the whole blast furnace comprehensive mathematical models based on multiphase multicomponent theory have been successfully applied with new features and continuous improvements [10–18]. Thus, we proposed to analyze, using a detailed mathematical model, a combined injection practice of H₂, O₂ and CO₂ to take the advantages of the expected increasing of the raceway temperature by the H₂ combustion. This excess energy is used to promote CO₂ conversion through fast solution loss reaction with the pulverized coal in the raceway, avoiding unburned coal accumulation and allowing suitable slagging practice [19,20]. Accordingly, we propose the concept of simultaneous injection of H₂, O₂ and CO₂ recycling into the tuyere of the furnace, as shown in Fig. 1. For this practice, external sources of hydrogen and oxygen rich gas are needed while CO₂ is obtained by treating the blast furnace exit gas. With this practice, the BF off gas is enriched and its calorific value improved. Besides, it is expected that the kinetics of pulverized coal combustion in the raceway is enhanced and the temperature of the lower part of the furnace kept under control, since combustion of H₂ will provide additional energy. In contrast, the enhanced water gas and solution loss reactions will consume this excess energy, depending on the amount of CO₂ injected. The tiny balance of these reactions will keep suitable temperature distributions and materials flow in the blast furnace. Fig. 2 shows the expected mechanism and flow pattern, which is able to enhance the pulverized coal reactions within the raceway replacing coke reactions in this zone. Several blast furnaces

![Fig. 1 - Concept of mix injection of H₂, O₂ in raceway of the blast furnace and CO₂ recycling technology.](image-url)
Conventional route

\[2C(pc) + O_2(g) \rightarrow 2CO(g)\]
\[\Delta H = -197030 \text{kJ mol}^{-1} O_2\]

New route with \(H_2\) injection

\[2H_2(g) + O_2(g) \rightarrow 2H_2O(g) + 2C(pc) \rightarrow 2H_2(g) + 2CO(g)\]
\[\Delta H = -197030 \text{kJ mol}^{-1} O_2\]

Fig. 2 – Raceway reactions modifications for gaseous injection of \(H_2\), \(O_2\) and recycling \(CO_2\).

Fig. 3 – Phases and respective interactions assumed in the proposed model.
around the world have been operated with injection rates higher than 180 kg·thm⁻¹. Nevertheless, further increase on the injection rates are limited due to materials flows within the lower part of the furnace and cohesive zone. The unburned powder accumulation and high viscosity slag formed during ash melt deteriorate the permeability of the dropping zone leading to unstable conditions [13,20]. When injection of mix gases is carried out in the blast furnace, the temperature and gas flow inside the raceway are drastically changed. These effects on the raceway region define the whole furnace operation leading to mutual interactions of the phases and chemical species. Special concern is related with the cohesive zone shape and position, which play important role on the granular zone behavior regarding the fluid flow, heat transfer and reaction rates. The multiphase multicomponent model is able to take in to account these phenomena and quantify the yield of raw materials. In this paper we tested the model for an actual operation with high injection of PC (220 kg·thm⁻¹) and simulated scenarios of higher injection (250 kg·thm⁻¹) to demonstrate the new proposed operation taking the advantages of hydrogen injection in the raceway region. It is important to notice that, although hydrogen rich gas has been previously tested on the granular zone [7,14], we proposed a very new concept, which not only improve the reducing zone efficiency, but use the advantages of the thermal control of the lower part of the furnace with the addition of oxygen and hydrogen to enhance the exothermic reactions. This tiny control allows the smooth operation of the whole furnace.

2. Methods

2.1. Modeling principles

The mathematical model proposed in this study is assumed three-dimensional and analyses the in-furnace region of the packed bed. The domain is assumed from the slag surface in the hearth up to the burden surface in the throat. Five phases are modeled: gas, granular solids (coké, sinter, pellets, granular iron ore), hot metal, slag, and pulverized coal (PC). In the gas phase are included the newly considered chemical species and chemical reactions. Fig. 3 shows the continuous and dispersed phases and their mutual physical and chemical interactions assumed in this model. All phases are treated simultaneously due to mutual interactions and inter-phase mass, momentum and energy exchanges. Similar approach has been discussed in previous literature, which confirms the adequacy of this theory to be applied for simulating the BF process [3–5,13–22]. The mix injection of hydrogen, pulverized coal, oxygen and carbon dioxide recycling within the raceway, however, is proposed and demonstrated the technological feasibility for the first time in this study.

2.1.1. General conservation equations treated in the model

A general formulation for the blast furnace process is proposed. Thus, the governing equations of all phases, that form a large set of strongly coupled non-linear differential equations, are solved simultaneously. In this model, conservation
Fig. 4 – Tridimensional raceway sector evidencing gas phase trajectories and burden radial distribution for the simulation of base case (PC: 220 kg thm\(^{-1}\)).

Fig. 5 – Off gas probe measurements for temperature and gas composition compared with model calculations for PC: 220 kg thm\(^{-1}\).
Table 2 – Main chemical reactions considered in this multiphase model.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{C} + \frac{1}{2} \text{O}_2$ &amp; $\rightarrow \text{CO}$</td>
<td></td>
</tr>
<tr>
<td>$\text{C} + \text{H}_2$ &amp; $\rightarrow \text{CH}_4$</td>
<td></td>
</tr>
<tr>
<td>$\text{C}_2\text{H}_4 + \text{O}_2$ &amp; $\rightarrow 2\text{CO} + 3\text{H}_2$</td>
<td></td>
</tr>
<tr>
<td>$\text{C}_3\text{H}_6 + \frac{1}{2} \text{O}_2$ &amp; $\rightarrow 2\text{CO}_2 + 3\text{H}_2$</td>
<td></td>
</tr>
<tr>
<td>$\text{SiO}_2 + \text{CO}_2$ &amp; $\rightarrow 2\text{SiO} + \text{CO}$</td>
<td></td>
</tr>
<tr>
<td>$\text{Si}_2\text{O}_3 + \text{SiO}_2$ &amp; $\rightarrow 2\text{SiO}_2$</td>
<td></td>
</tr>
<tr>
<td>$\text{Si}_2\text{O}_3 + \text{SiO}_2$ &amp; $\rightarrow 2\text{SiO}_2$</td>
<td></td>
</tr>
</tbody>
</table>

Note: the stoichiometric coefficients depend on the elemental analysis of the carbonaceous materials (i.e., coke, small coke and pulverized coal).

- $\text{H}_2\text{O} + \text{C}$ & $\rightarrow \text{CO} + \text{H}_2$ |
- $\text{MnO}_2 + \text{C}$ & $\rightarrow \text{MnO} + \text{CO}_2$ |
- $\text{SiO}_2 + \text{C}$ & $\rightarrow \text{Si} + \text{CO}_2$ |
- $\text{Si}_2\text{O}_3 + \text{SiO}_2$ & $\rightarrow 2\text{SiO}_2$ |

Gaseous reactions

- $\text{C}_2\text{H}_4 + \frac{1}{2} \text{O}_2$ & $\rightarrow 2\text{CO} + 3\text{H}_2$ |
- $\text{C}_2\text{H}_6 + \frac{1}{2} \text{O}_2$ & $\rightarrow 2\text{CO} + 3\text{H}_2$ |
- $\text{SiO}_2 + \text{CO}_2$ & $\rightarrow 2\text{SiO} + \text{CO}$ |
- $\text{Si}_2\text{O}_3 + \text{SiO}_2$ & $\rightarrow 2\text{SiO}_2$ |

The phases are composed of various chemical species and the general conservation equation is used to calculate the phase motion, the phase energy and the mass fraction of chemical species in each phase. The list of all five phases and their respective species treated in this model is presented in Table 1 together with their variables accounting for momentum and energy conservations.

2.1.2. Boundary conditions and numerical approach used in this study

The boundary conditions assumed in this study use the observed information of the dynamics of the reactor and measured parameters on the actual operation practice. Therefore, the boundary conditions are applied on the boundary of the computational domain delimited at the bottom by the slag surface, at the top by the burden surface profile and by lateral walls. At the top, the gas phase is assumed as fully developed flow and solid inflow is modeled based on the inflow rate given by local solid mass consumption due to chemical reactions and melting or gravity driven flows. At the tuyere injection, inlet of blast, additional oxygen, hydrogen or fuel gas and pulverized coal are given by their inflow rates. The blast flow rate and gaseous fuel injection are fixed while pulverized coal injection is iteratively calculated to reach the aimed pulverized coal injection rate, which are specified at the beginning of the iterative calculation. The blast temperature and pulverized coal temperature inlet are specified as fixed values throughout the calculation. At the side wall, mass fluxes across the wall are assumed null while heat loss is allowed by setting an overall cooling heat transfer coefficient calculated based on the cooling system data. For the gas velocity it is assumed null
values perpendicular and tangential to the furnace wall. The solid tangential velocity on the wall surface assumes coulomb attrition law with a specified coefficient of 0.3 and the normal force is calculated using the local solid pressure, which is lumped into the source terms of the momentum equations of solid phase in the nearest volume of the wall surface and acts always as resistance term to the solid motion near the wall surface allowing sleep granular motion. The burden distribution is determined by the relative volume fractions of the inlet solids and their average diameter. The numerical method used to solve the transport equations is based on the finite volume method (FVM) formulated for a general non-orthogonal coordinate system [26–28]. The numerical mesh is constructed based on a body fitted coordinate system which allows accurate description of the blast furnace wall shape [26–28]. To solve the governing (momentum) equations of continuous phases the SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm is applied on a staggered grid for covariant projections of the velocities and the numerical coefficients of the discretized equations are determined by using the power low scheme [26–28]. The convergence is assumed for momentum and energy equations of the five phases with the maximum relative error less than $10^{-3}$ while for all chemical species overall error less than 1% were accepted for finishing the calculations.

2.1.3. Treatment of the source terms due to mutual interactions ($S_{ih}$)
The treatment of the source terms is the key step of the accuracy of the multiphase model concept. The source terms in the conservation equations take into account chemical reactions, phase transformations, momentum exchange, external force, etc. [14–22]. The continuity and species conservation equations have mass sources due to chemical reactions and phase transformations. Enthalpy sources arise from interphase heat transfer, heat of reaction and sensible heat accompanied with the mass transfer due to chemical reactions and phase transformations [14–17]. The formulations for the phase interactions and chemical reactions have been published in previous reports [3–5,11–25]. The chemical reactions considered in this model are presented in Table 2. The momentum and energy sources are considered by taking into account the solid layer structure and cohesive zone formed depending on the soft-melting properties of individual burden [13,14].

| Table 3 – Comparisons of operational parameters calculated and model predictions for mix injections H2, O2 and CO2 with PC. |
|---------------------------------------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| Productivity (thm day$^{-1}$ m$^{-3}$ of working volume) | 2.40 | 2.40 | 2.60 | 3.20 | 3.32 | 3.50 |
| Oxygen enrichment (%) (input) | 7.34 | 7.30 | 7.34 | 7.34 | 7.34 | 7.34 |
| Blast (Nm$^3$ thm$^{-1}$) (input) | 944 | 944 | 843.3 | 641.2 | 627.2 | 622.3 |
| H2 injection (Nm$^3$ thm$^{-1}$) | – | – | 93.6 | 224.7 | 146.5 | 148.3 |
| CO2 injection (Nm$^3$ thm$^{-1}$) | – | – | – | – | 26.6 | 28.4 |
| O2 injection (Nm$^3$ thm$^{-1}$) | – | – | 46.1 | 110.6 | 72.2 | 78.2 |
| Raceway maximum temperature (°C) | 2091 | – | 2272 | 2472 | 2241 | 2413 |
| Si | 0.30 | 0.33 | 0.38 | 0.50 | 0.27 | 0.35 |
| Slag rate (kg thm$^{-1}$) | 250.5 | 254.4 | 242.8 | 247.5 | 253.5 | 252.3 |
| CaO/SiO2 | 1.29 | 1.25 | 1.43 | 1.32 | 1.26 | 1.24 |
| CaO (%) | 43.9 | – | 45.4 | 44.6 | 43.9 | 44.2 |
| MgO (%) | 8.8 | – | 9.1 | 8.7 | 8.5 | 8.6 |
| Al2O3 (%) | 13.2 | – | 13.7 | 13.2 | 12.5 | 12.2 |
| Off gas (Nm$^3$ thm$^{-1}$) | 1569 | 1515.8 | 1578.6 | 1513.3 | 1398.5 | 1422.1 |
| CO2/CO + CO2 | 0.42 | 0.46 | 0.41 | 0.41 | 0.45 | 0.46 |
| CO2 (Nm$^3$ thm$^{-1}$) | 306.4 | – | 291.4 | 274.5 | 301.4 | 295.3 |
| CO (Nm$^3$ thm$^{-1}$) | 422.4 | – | 423.5 | 394.7 | 359.4 | 356.4 |
| H2 (Nm$^3$ thm$^{-1}$) | 60.2 | – | 96.5 | 135.5 | 84.4 | 82.3 |
| N2 (Nm$^3$ thm$^{-1}$) | 646.9 | – | 579.4 | 443.1 | 429.6 | 423.2 |
| Temperature (°C) | 164.8 | 156.5 | 169.2 | 182.4 | 170.9 | 169.3 |
| Coke consumption (kg thm$^{-1}$) | 219.9 | 215.5 | 216.4 | 201.3 | 201.8 | 200.3 |
| Small coke (kg thm$^{-1}$) | 65.3 | 65.0 | 65.9 | 56.3 | 25.5 | 24.3 |
| PC (kg thm$^{-1}$) | 219.4 | 220.0 | 219.5 | 220.1 | 219.8 | 219.6 |
| Coke solution loss (kg C thm$^{-1}$) | 65.1 | – | 59.3 | 68.5 | 70.3 | 69.2 |
| Coke water gas reaction (kg C thm$^{-1}$) | 40.8 | – | 47.5 | 43.8 | 32.2 | 33.3 |
| Coke direct reduction (kg C thm$^{-1}$) | 43.6 | – | 43.5 | 52.3 | 50.8 | 48.3 |
| PC solution loss (kg C thm$^{-1}$) | 60.5 | – | 54.1 | 36.1 | 40.6 | 43.2 |
| PC water gas reaction (kg C thm$^{-1}$) | 68.6 | – | 69.6 | 79.3 | 75.3 | 76.4 |
| PC direct reduction (kg C thm$^{-1}$) | 0.0 | – | 0.2 | 0.8 | 2.5 | 2.8 |
| PC combustion efficiency (%) | 99.6 | – | 99.7 | 100 | 100 | 100 |
| Specific carbon emission (kg C thm$^{-1}$) | 385.9 | – | 383.1 | 358.7 | 339.7 | 336.2 |

PC, pulverized coal; thm, ton of hot metal (pig iron). Castro et al.
Table 4 – Calculated operational parameters for H2 and CO2 mix injection with high PC injection.

<table>
<thead>
<tr>
<th></th>
<th>Only H2 injection</th>
<th>CO2 and H2 injections</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Case 5</td>
<td>Case 6</td>
</tr>
<tr>
<td>Productivity (thm day−1 m−3 of working volume)</td>
<td>2.63</td>
<td>2.72</td>
</tr>
<tr>
<td>Oxygen enrichment (%) (input)</td>
<td>9.96</td>
<td>9.96</td>
</tr>
<tr>
<td>Blast (Nm3 thm−1) (input)</td>
<td>859.5</td>
<td>833.3</td>
</tr>
<tr>
<td>H2 injection (Nm3 thm−1)</td>
<td>0</td>
<td>0.8</td>
</tr>
<tr>
<td>CO2 injection (Nm3 thm−1)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>O2 injection (Nm3 thm−1)</td>
<td>0</td>
<td>4.4</td>
</tr>
<tr>
<td>Raceway maximum temperature (°C)</td>
<td>2106</td>
<td>2129</td>
</tr>
<tr>
<td>Si</td>
<td>0.32</td>
<td>0.28</td>
</tr>
<tr>
<td>Slag rate (kg thm−1)</td>
<td>238</td>
<td>246</td>
</tr>
<tr>
<td>CaO/SiO2</td>
<td>1.47</td>
<td>1.32</td>
</tr>
<tr>
<td>CaO (%)</td>
<td>45.7</td>
<td>44.3</td>
</tr>
<tr>
<td>MgO (%)</td>
<td>9.4</td>
<td>9.0</td>
</tr>
<tr>
<td>Al2O3 (%)</td>
<td>13.7</td>
<td>13.3</td>
</tr>
<tr>
<td>Off gas (Nm3 thm−1)</td>
<td>1481</td>
<td>1449.8</td>
</tr>
<tr>
<td>CO2/(CO + CO2)</td>
<td>0.44</td>
<td>0.42</td>
</tr>
<tr>
<td>CO2 (Nm3 thm−1)</td>
<td>299.7</td>
<td>300.0</td>
</tr>
<tr>
<td>CO (Nm3 thm−1)</td>
<td>398.8</td>
<td>391.7</td>
</tr>
<tr>
<td>H2 (Nm3 thm−1)</td>
<td>63.9</td>
<td>66.8</td>
</tr>
<tr>
<td>N2 (Nm3 thm−1)</td>
<td>546.1</td>
<td>559.2</td>
</tr>
<tr>
<td>Coke consumption (kg thm−1)</td>
<td>193.5</td>
<td>193.1</td>
</tr>
<tr>
<td>Small coke (kg thm−1)</td>
<td>53.1</td>
<td>52.9</td>
</tr>
<tr>
<td>PC – pulverized coal (kg thm−1)</td>
<td>249.4</td>
<td>249.1</td>
</tr>
<tr>
<td>Coke solution loss (kg Cthm−1)</td>
<td>57.9</td>
<td>55.4</td>
</tr>
<tr>
<td>Coke water gas reaction (kg Cthm−1)</td>
<td>36.5</td>
<td>34.8</td>
</tr>
<tr>
<td>Coke direct reduction (kg Cthm−1)</td>
<td>45.1</td>
<td>43.6</td>
</tr>
<tr>
<td>CO solution loss (kg Cthm−1)</td>
<td>47.2</td>
<td>47.2</td>
</tr>
<tr>
<td>CO water gas reaction (kg Cthm−1)</td>
<td>65.1</td>
<td>75.2</td>
</tr>
<tr>
<td>CO direct reduction (kg Cthm−1)</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>PC combustion efficiency (%)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Net carbon emission (kg Cthm−1)</td>
<td>378.5</td>
<td>369.1</td>
</tr>
</tbody>
</table>

PC, pulverized coal; thm, ton of hot metal (pig iron).

 Castro et al.

2.2. Model validation using industrial data of large BF

The proposed model has been previously validated by using measured data obtained in an industrial blast furnace which has working volume of 3970 m³ and instrumentations based on temperature and gas composition probes at the burden surface level [4,18,24]. The burden distribution is assumed in the model for the charging materials with radial distribution of mean solid diameter and their volume fractions. Fig. 4 shows steady state results for tridimensional raceway sector of influence and the burden materials distribution charged with their radial mean diameter distribution and charging pattern for the base case of 220 kg thm−1 of pulverized coal and the respective inner temperature distribution and gas flow pattern. The charging distribution is iteratively calculated together with the temperature and gas flow pattern. The iterative process is driven by the measured temperature and gas composition profiles obtained by probing at the burden surface with small corrections for the radial distributions of the average burden particle diameters and materials volume fractions. As observed, central charging of granular coke was promoted and the temperature and gas flow reflect this charging condition and vice versa. In order to validate the model, averaged input data of 24 h operation was used and the probe measurements for radial distribution temperature and gas composition were monitored in a total of 24 runs corresponding 24 interval of 1 h. The averaged temperature and composition of CO and CO2 predicted by the model were used to correct the burden distributions patterns. The final accepted calculated results were compared with the probe data and showed excellent concordance, as can be seen in Fig. 5(a) and (b), respectively. Besides, the general trend of the monitored data reflects the central gas flow operation practiced in the charge system with granular coke charged mostly at the central region of the furnace.

3. Results and discussions

3.1. Model verification for actual BF practice

Table 3 (column 1 and 2) summarizes the comparison for model predictions of global parameters and averaged industrial data of the furnace used in this study as the reference case. As can be observed, good agreement was obtained for all compared parameters. The model was applied for two sets of pulverized coal injections mixed with fuel gas. The cases 1–4 are the actual injection practice of pulverized coal with the newly suggested practice of additional injections of H2, O2, and CO2, while cases 5–10 are 250 kg thm−1 of PC mixed with H2, O2 and CO2 injection. Table 3 shows the operational parameters
Fig. 6 – Steady burden distributions predictions for mix injection of H₂, O₂ and CO₂ with PC: 220 kg thm⁻¹.

Fig. 7 – Calculated burden distributions for mix injection of H₂, O₂ and CO₂ with PC: 250 kg thm⁻¹.
Fig. 8 – Predicted gas flow pattern and temperature distribution for a raceway vertical plane for mix injection of H₂, O₂ and CO₂ with PC: 220 kg thm⁻¹.

Fig. 9 – Calculated gas flow pattern and temperature distribution for a raceway vertical plane for mix injection and PC: 250 kg thm⁻¹.
Fig. 10 – Calculated cohesive zone location and solid flow descending pattern for a raceway sector for mix injection and PC: 220 kg thm⁻¹.

Fig. 11 – Calculated shape of cohesive zone and solid flow descending pattern for a raceway sector for mix injection and PC: 250 kg thm⁻¹.
predictions for the 220 kg thm\(^{-1}\) injection cases, while Table 4 shows the parameters for 250 kg thm\(^{-1}\) injection cases. As can be observed, for all cases of H\(_2\), O\(_2\) and CO\(_2\) injection, the granular coke or small coke charged at the burden decreased due to the replacement of granular coke by hydrogen fuel. Tables 3 and 4 also presented the computed values of carbon consumption on the lump coke and pulverized materials for solution loss reactions and water gas reactions, the main reactions that can take place in the PC replacing granular coke. As observed, the solution loss and water gas reactions were enhanced with the mixed injections of H\(_2\), O\(_2\), CO\(_2\) and PC in the tuyeres. It is very important to mention that for all cases of gas injection the net specific carbon emission on the blast furnace off gas decreased, which confirmed the effectiveness of these operation techniques to reduce greenhouse emissions, the main focus of this study. The reduction of the carbon emissions is attributed to the combined effect of coke reduction, CO\(_2\) recycling and enhancement of the blast furnace efficiency. It is also worthy to mention that the productivity of the blast furnace largely increased due to the additional oxygen injection and the replacement of the granular coke into the burden, which relatively increase the iron-bearing materials volume fractions. Figs. 6 and 7 show the burden distributions used in these calculations. As can be observed, the gas injection practice for the scenarios proposed did not required significant changes in the charging practice, which is a great advantage. Only the ratio of iron bearing materials and coke was changed to attain the solid inflow rates imposed by the increase in the productivity and therefore only the relative positions of the volume fractions curves shift upward to account for the mass flow rates and increase of the ore to coke ratios on the burden.

3.2. Comparison of the in-furnace variables for mix injection in the raceway

In this section, the model is applied to investigate new operational conditions of H\(_2\), O\(_2\) and CO\(_2\) mixed with higher injection rates and compared with base case. Two sets of scenarios were design: (i) actual operational practice of 220 kg thm\(^{-1}\) of pulverized coal injection with additional injection of H\(_2\), O\(_2\) and CO\(_2\) in the raceway and (ii) increasing the pulverized coal injection to 250 kg thm\(^{-1}\) and additional injection of H\(_2\), O\(_2\) and CO\(_2\) in the raceway. The results discussed in this section were obtained by iterative calculations until stable phase flows and temperature pattern are reached and therefore represents predicted feasible operational conditions for the blast furnace operation. Fig. 8 shows the temperature and gas flow pattern for the first set of scenarios. As can be observed cases 1 and 2 (only H\(_2\) and O\(_2\) injections) considerably increased the temperature of raceway region and slowly increase the drooping zone temperature region but the changes in the shaft region temperature were negligible. Cases 3 and 4 (combined injection of H\(_2\), O\(_2\) and CO\(_2\)) allows the CO\(_2\) recycling by using the lower part of the blast furnace excess energy and enhance the productivity with lower blast rate (see Tables 3 and 4). As can be observed in all cases the temperature patterns inside of the blast furnace are compatible with stable operation and therefore could be practiced in this reactor with the advantage of considerably decreasing the consumption of granular reducing agent and specific carbon emissions (see Tables 3 and 4). Fig. 9 shows the temperature patterns and gas flow distribution in a vertical plane passing through the raceway for the second set of scenarios with pulverized coal 250 kg thm\(^{-1}\). As can be observed, cases 6–7 (only H\(_2\) and O\(_2\) injection), similarly to previous calculation of 220 kg thm\(^{-1}\), increased the temperature due to the heat input promoted by H\(_2\) combustion. Cases 9–10 restored the temperature and gas flows by using the excess energy of H\(_2\) combustion to reform the CO\(_2\) injected. Figs. 10 and 11 shows the solid descending flow paths, residence time of the lump materials and the calculated position of the cohesive zone for the two sets of scenarios considered in this study. In this model the cohesive zone definition is not predetermined, instead, the softening-melting burden parameters are used, mainly the initial softening and melting temperature, interval of melting temperature, maximum pressure drop and the degree of shrinkage obtained in laboratory burden characterization that are used in all sub-models of gas flow resistance, heat transfer in the mushy zone and chemical reactions. Therefore, the actual position of the cohesive zones, thickness and shape are the result of coupled phenomena taking place in the whole blast furnace process. In all simulations the same set of burden materials parameters were used (T\(_{\text{sm}}\) – temperature of starting melting of 1228 °C, shrinkage factor of 0.33 and interval of melting temperature for maximum pressure drop of 185 °C). As can be observed, as the amount of injection gas was increased the equilibrium position and shape of the cohesive zones shift up and became thicker. Fig. 11 presents similar pattern and showed that the residence time of the granular materials in the shaft region decreased considerably due to increase in the productivity. For all scenarios proposed in this study, the model predicted the necessary parameters to be safety carried out in the blast furnace practice under mixed injection of H\(_2\), O\(_2\) and CO\(_2\) with PC. Therefore, all of the scenarios proposed could be used to enhance the blast furnace operation combining high productivity, simultaneous injection of pulverized coal, H\(_2\), O\(_2\) and CO\(_2\) with drastic decreasing of the blast rate, granular solid reducing agent and CO\(_2\) emissions. These features definitively would enhance the blast furnace performance not only from the perspective of productivity but also from the point of view of cleaner technology development of ironmaking route.

4. Conclusions

We presented improvements of the multiphase mathematical model for simulating the blast furnace with new features and applied to predict the new furnace condition under mix injections of PC and gaseous fuel enriched on H\(_2\), O\(_2\) and CO\(_2\) with the aim of reaching new possibilities for the process with lower environmental impact. The improved model uses multiphase interactions formulated for momentum, energy and chemical species. The model takes into account simultaneously in all phases the new chemical reactions occurred in the process due to new materials injections. The model predictions were compared favorably with a continuous monitoring BF data measured for a smooth operation period. In the sequence, new operation practice techniques based on higher mix
injection of PC and rich hydrogen, oxygen and carbon dioxide fuels were simulated. The model predictions newly indicated that important decrease in the granular coke consumption in the BF process is possible by proposing new mix injections of 250 kg/tm⁻¹ of PC and correspondent H₂ and O₂ injection to keep raceway temperature and dropping zone with stable liquids and gas flow conditions. Furthermore, it was found that CO₂ injection is possible due to high temperature developed with H₂ and O₂ injection and for all simulated results the model indicated that lower carbon emissions can be achieved by the proposed operational conditions.

Conflicts of interest

The authors declare no conflicts of interest.

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