



Original Article

Analysis of the combined injection of pulverized coal and charcoal into large blast furnaces

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ABSTRACT

The simultaneous injection of pulverized coal and charcoal in the blast furnace has recently received remarkable attention due to its potential to decrease the coke consumption and increase productivity. This paper is focused on modeling the simultaneous injection of pulverized coal and charcoal into the blast furnace through the tuyeres with oxygen enrichment. This model treats the blast furnace as a multi-phase reactor and six phases are considered simultaneously, namely: gas, lump solids (lump iron ore, sinter, pellets, coke and small coke), hot metal, molten slag, pulverized coal and charcoal. Conservation equations of mass, momentum, energy and chemical species are solved simultaneously based on the finite volume method. The model is validated with a base case of actual operation using 215 kg/thm of pulverized coal injection and afterwards mixed injection of coal and charcoal are simulated for injection rate of 250 kg/thm. Model results indicated that the productivity of the blast furnace could be increased up to 25% with simultaneous injection combined with oxygen enrichment.

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1. Introduction

In the present status of development the technology to produce hot metal in the steel industry is mainly based on the blast furnace-BOF processes route. However, this route is recognized as intensive energy consuming and demands high quality of raw materials such as lump coke, pellets and sinter. In the integrated route of crude steel production the blast

furnace is responsible for around 70% of total energy input and about 60% of the total cost of pig iron production in this process is due to the reducing agent used in the blast furnace as lump coke or pulverized coal injected through the tuyeres. Therefore, tremendous efforts have been made in order to reduce the reducing agent rate of the blast furnace, or at least, replace the coke consumption by less precious materials injected through the blast furnace tuyere [1–6]. Based on this perspective, the simultaneous injection of pulverized

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Table 1 – Compositions of reducing agents and thermophysical properties used in this study.

(Mass%)	Coke	Pulverized coal (PCI)	Pulverized charcoal (PCH)
C (fixed)	87.20	72.20	71.24
Volatile matter	1.00	19.50	25.80
Humidity	0.15	0.01	0.01
SiO ₂	6.52	5.70	1.10
Al ₂ O ₃	3.61	2.12	0.11
MgO	0.18	0.01	
CaO	0.47	0.30	1.58
S	0.65	0.39	0.0022
FeS	0.22	–	–
P(P ₂ O ₅)	–	–	0.170
Na(Na ₂ O)	–	–	–
K(K ₂ O)	–	–	0.40
Ash	11.60	8.52	2.96
<i>Volatile matter (mass%)</i>			
C	74.40	68.30	72.00
N	8.40	4.50	7.35
H	12.60	25.20	16.50
O	4.60	2.00	4.15
<i>Thermo-physical properties used in this study</i>			
Average particle diameter (μm)	–	150	120
True density (kg/m ³)	1820	1545	1150
Particle porosity	0.45	0.7	0.85
Pore tortuosity	0.8	0.8	0.9
Thermal conductivity (W/m K)	–	0.6	0.6
Calorific value (kJ/kg)	34,276	32,415	31,162

charcoal and coal in the blast furnace tuyeres has the attractive perspective to improve the pulverized coal combustion within the raceway in addition to the already demonstrated environmental benefits that can be obtained by capturing CO₂ from the atmosphere in a relatively short cycle (about 7 years), if one considers the charcoal produced by forestation. Therefore, it is a competitive technology for producing hot metal, especially for regions where the climate is favorable to the plantation of biomass and will demand further increase on the steel production by constructing new blast furnaces in near future. The combustion rate of charcoal is quite high compared with those of coal and coke [4–8]. When pulverized charcoal is injected into the raceway, it combusts first and furnishes heat and CO₂ which in turn, is used for gasification of the pulverized coal by increasing solution loss reaction in addition to partial and full combustion directly with the blast enriched with oxygen. Composition of charcoal is quite different from that of coal usually injected into the blast furnace [4–6]. The charcoal used in this study has very low ash, sulfur and silica content; however, volatile matter is usually higher, as shown in Table 1. The gas produced due to gasification reaction within the raceway has higher hydrogen content and lower ignition temperature is needed (around 700 °C). In addition, the technology for injection of pulverized coal already get maturity and several blast furnaces over the world have been continuously operated with pulverized coal rates around 200 kg/thm. However, there is clear limitation for further increases in the injection rates of pulverized coal mainly due to the gas and particles flows in the lower part of the furnace and unburned coal or ash that can remain in the raceway, which could deteriorate the permeability of this region leading to unstable operation. In the same hand, the pulverized

charcoal injection technology applied for small blast furnaces based on granular charcoal has entered in a stage of high technological development [2–4]. Aiming at contributing to clarify the in-furnace phenomena and show the feasibility of simultaneous injection, this paper focuses on the analysis of the coke based blast furnace process with simultaneous injection of charcoal and coal in the raceway in order to demonstrate the advantages of both technologies. The injection of charcoal into the blast furnace tuyere substitutes the coke charged from the blast furnace top and furnishes higher amount of hydrogen, which replace carbon monoxide as reducing gas in the shaft of the blast furnace. The hydrogen gas is a better reducing agent if compared with carbon monoxide and allows savings of energy by decreasing the amount of direct reduction which can take place in the lower part of the furnace. Several authors have addressed the multiple injections of carbonaceous materials into the blast furnace by theoretical and experimental analysis [1,4–9]. However, only detailed mathematical model based on fundamental phenomena is expected to fully consider the important aspects of simultaneous injection. In this paper a mathematical model of the blast furnace is proposed to simulate the blast furnace operation with simultaneous injection of pulverized charcoal and coal. The present model uses similar approach as those presented by Yagi et al. [10], Austin et al. [11,12] and Castro et al. [9,13,14], which applied multiphase theory to describe the motion, energy and chemical species of each phase inside the furnace. Although some hybrid models based on DEM (discrete element method) have been discussed [15–19], the multiphase theory is considered suitable and enough accurate to describe the actual operation of the blast furnace, since DEM approach has shown severe limitations to deal with realistic situation within the blast

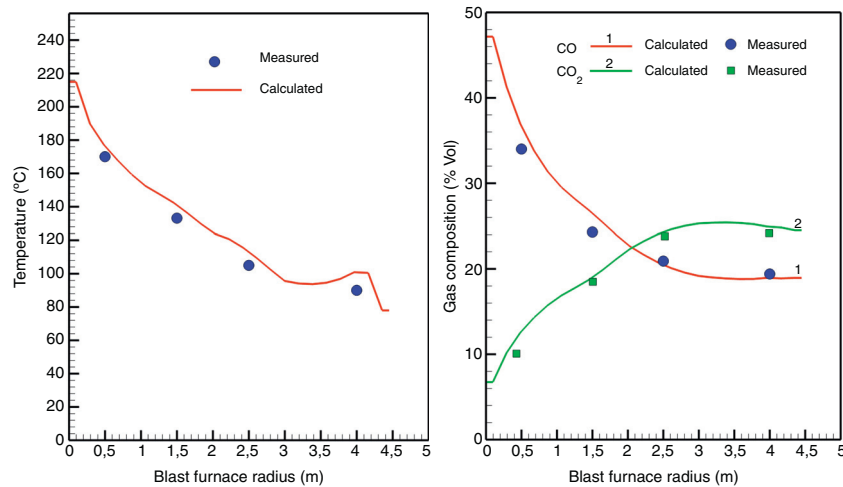


Fig. 1 – Comparison of the measured and calculated results of the probe data (base case for model validation).

furnace regarding to accurate calculations of physical changes of the particles due to reactions and melting, in addition to need of large memory and computation time that has limited to apply for a number of simulation cases. Therefore, the continuum approach is a better tool to evaluate the performance of the whole blast furnace process under multiple injection operation [10–15,20–22]. In this paper, the pulverized charcoal injection is treated as an independent phase due to the significant difference in the thermo-physical properties and phase interactions of momentum and energy compared with the pulverized coal phase. Also, kinetic rate equations are quite different between charcoal and coal. Therefore, in the present study a detailed model able to take into account particular phenomena and mechanism of simultaneous injection of pulverized coal and charcoal is used. Thus, this model aims to address new features of the simultaneous injection of pulverized coal and charcoal to the blast furnace and to investigate new operation possibilities, which could contribute to lower coke consumption and suggest new environmentally cleaner process operation techniques.

2. Modeling

2.1. Model approach

The mathematical model is three-dimensional and analyses the packed bed region within the blast furnace, from the slag surface in the hearth up to the burden surface in the throat. Six phases are treated: gas, lump solids (coke, sinter, pellets, lump ore), hot metal, slag, pulverized charcoal and pulverized coal. All phases are treated simultaneously due to mutual interactions. Thus, the governing equations of all phases, that form a large set of strongly coupled non-linear equations, are solved simultaneously. In this model, conservation equations of motion, energy and chemical species are considered and coupled with chemical reactions and physical properties. For

the sake of simplicity, all the conservation equations are represented in a compact form, as in Eq. (1).

$$\frac{\partial(\varepsilon_i \rho_i \phi_i)}{\partial t} + \text{div}(\varepsilon_i \rho_i \vec{V}_i \phi_i) = \text{div}(\varepsilon_i \Gamma_{\phi_i} \text{grad } \phi_i) + S_{\phi_i} \quad (1)$$

In this equation, ϕ is the dependent variable, expressing the component velocities for the phase momentum equations, the enthalpy for the phase energy equations and the chemical species for the phase continuity equations, i represents the phase being considered or the chemical species of each phase. ε and ρ are phase volume fraction and density, respectively. V and t are phase velocity field and time, respectively. Γ_{ϕ_i} is the effective transfer coefficient which represents effective dynamic viscosity in the momentum equations, effective thermal conductivity in the energy equations and effective diffusion coefficient of the chemical species in the materials equation of each phase. The source terms (S_{ϕ_i}) are due to inter-phase interactions that can appear through chemical reactions, surface interactions and external force [10–22]. Each considered phase is 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.

2.2. Source terms

The source terms in the conservation equations take into account chemical reactions, phase transformations, momentum exchange, external force and so on. The continuity and species conservation equations have mass sources due to chemical reactions and phase transformations. Enthalpy sources arise from inter-phase heat transfer, heat of reaction and sensible heat accompanied with mass transfer due to chemical reactions and phase transformations. The formulations for the phase interactions and chemical reactions have been published in previous reports [10–15]. This model considers the pulverized charcoal injected through a separated lance into the raceway channel. The charcoal injected through the blast furnace tuyeres is mixed with the gas stream and, in

Table 2 – Operational parameters and model validation.

	Base		Scenario 1	Scenario 2	Scenario 3
	Calculated	Measured	Calculated	Calculated	Calculated
Productivity (thm/day/m ³ working vol.)	2.27	2.26	2.42	2.66	2.92
Oxygen enrichment (%) (input parameter)	7.71	7.70	8.76	12.04	14.2
Blast (N m ³ /thm) (input parameter)	989.0	989.0	926.2	846.6	771.1
Blast temperature (°C) (input parameter)	1145	1145	1145	1145	1145
Si (%)	0.25	0.29	0.31	0.20	0.19
C (%)	4.79	4.65	4.79	4.80	4.78
Slag rate (kg/thm)	253	258	248.2	253.8	244.8
CaO/SiO ₂	1.16	1.20	1.15	1.10	1.12
CaO (%)	39.60	40.5	41.05	40.3	41.1
MgO (%)	8.70	8.40	9.01	8.81	9.08
Al ₂ O ₃ (%)	14.20	13.70	13.83	14.01	12.78
Off gas (N m ³ /thm)	1575	1584	1512	1439	1365
CO ₂ /(CO + CO ₂) (%)	52	48	52	54	54
Coke consumption (kg/thm)	207.60	208.5	204.2	187.7	186.9
Small coke (kg/thm)	64.10	65.1	63.6	43.7	41.4
PCI (kg/thm)	214.60	215.0	148.9	214.8	149.1
PCH (kg/thm)	–	–	64.50	34.50	99.40
Coke solution loss (kg C/thm)	79.90	–	86.20	82.50	86.98
PCI solution loss (kg C/thm)	24.50	–	21.7	24.5	16.0
PCH solution loss (kg C/thm)	–	–	7.35	2.50	6.40
PCI combustion efficiency (%)	99	–	100	100	100
PCH combustion efficiency (%)	–	–	100	100	100
Carbon emission (kg/thm)	377.34	–	370.82	368.6	370.2

PCI, pulverized coal injection; PCH, pulverized charcoal injection; thm, ton of hot metal.

contact with oxygen, combusts partially and the volatile matter evolves in the interior of the raceway and finally almost complete combustion in the raceway is achieved [8]. The unburned pulverized coal or ash continues to react and melt down when the particle temperature is higher than the melting temperature and enough heat is supplied. The chemical

reaction models for pulverized charcoal and coal used in this study have similar rate expressions; however, the parameters of reactivity and inner particle structure are quite different, which gives high difference in reaction rates [6,7]. The thermo-physical properties used in this model are presented in Table 1.

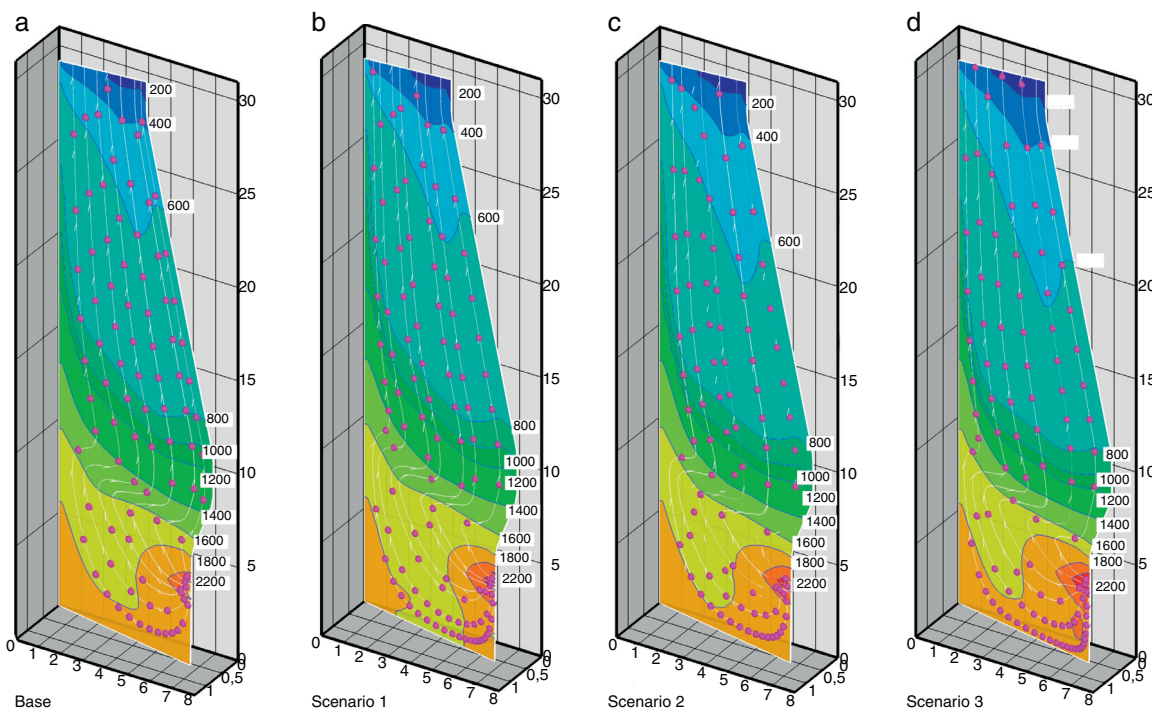


Fig. 2 – Temperature distributions and gas flow pattern for the scenarios considered in this simulation study.

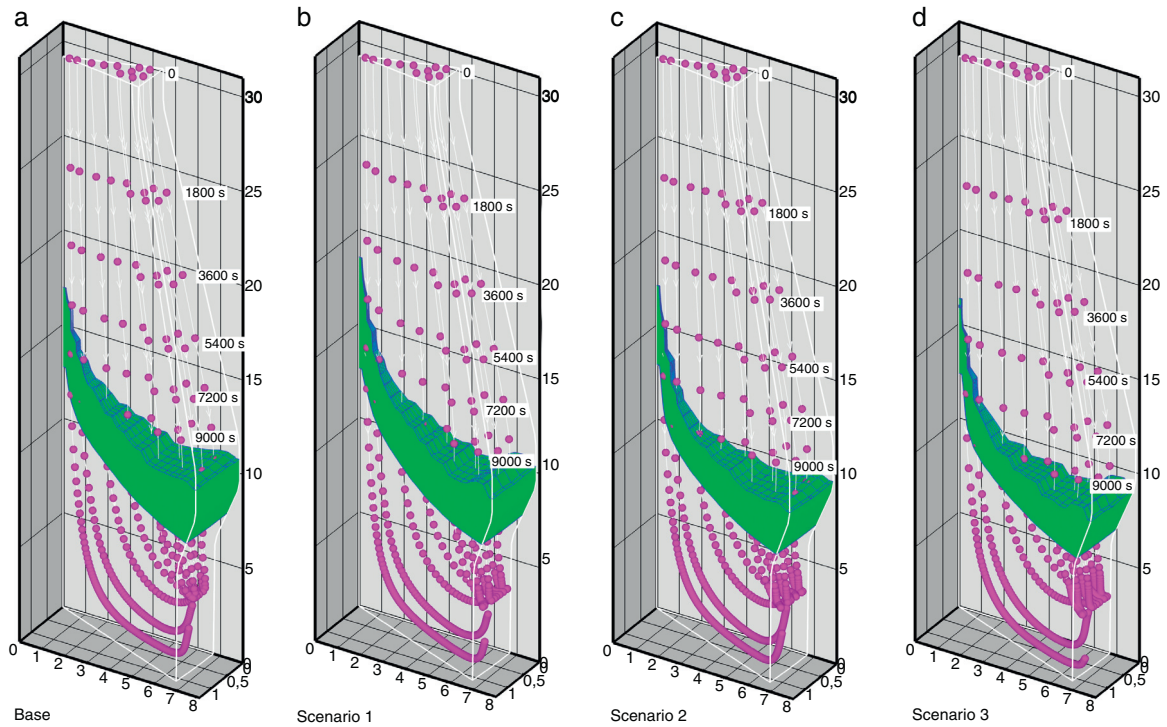


Fig. 3 – Solid flow patterns and cohesive zone locations and shapes for the scenarios analyzed.

2.3. Boundary conditions, assumptions and numerical features

The boundary conditions were applied on the boundary of the computational domain surrounded at the bottom by the slag surface, at the top by the burden surface and by lateral

walls. At the top, the gas phase is assumed as fully developed flow while solid inflow is modeled assuming no gradient velocity, with the inflow rate given by solid mass consumption due to chemical reactions and melting. At the tuyere inlet of blast, additional oxygen and pulverized coal are given by their inflow rates. The blast flow rate is fixed and pulverized

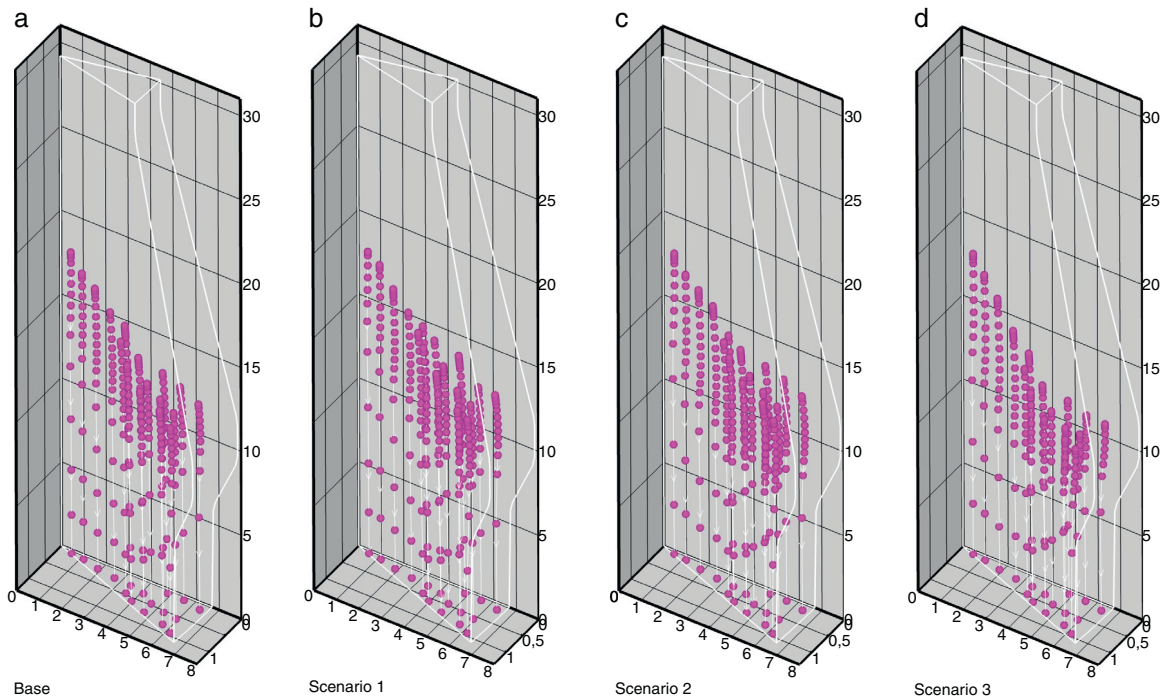


Fig. 4 – Liquid hot metal flow time lines for the scenarios analyzed in this study.

coal and charcoal are iteratively calculated to reach the aimed pulverized coal and charcoal injection rates, which are specified at the beginning of the iterative calculation. The blast temperature is specified as a fixed value throughout the calculation. At the side wall, momentum and mass fluxes across the wall are assumed null while heat transfer is allowed by setting an overall heat transfer coefficient. 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. 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 [23]. The numerical mesh is constructed based on a body fitted coordinate system which allows accurate description of the blast furnace wall shape [23]. 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 configuration for covariant projections of the velocities and the numerical coefficients of the discretized equations are determined by using the power law scheme [23–25].

3. Results and discussion

3.1. Model validation with industrial blast furnace data

The proposed model was verified by using measured data obtained in an industrial blast furnace which has working volume of 3970 m³ and instrumentations based on temperature probes at the burden surface level. The burden distribution is assumed in the model for the charging materials with radial distribution of mean solid diameter and their volume fractions. In order to validate the model input data of 24 h operation was used and the probe measurements for radial distribution temperature and gas composition were recorded in a total of 24 runs corresponding 24 interval of 1 h. The temperature and composition of CO and CO₂ predicted by the model were compared with the probe data and showed excellent accordance, as can be observed in Fig. 1(a) and (b), respectively. Table 2 summarizes the comparison for model predictions of global parameters and industrial data. As can be observed, good agreement was obtained for all parameters compared.

3.2. Comparison of the in-furnace states under multiple injection

In this section, the model is applied to investigate new operational conditions with higher injection rates and compared with base case. Three simulation scenarios were considered: Scenario 1: maintaining the actual injection rate and substitutes 65 kg/thm of pulverized coal by same amount of pulverized charcoal; Scenario 2: increasing the injection rate to 250 kg/thm by using pulverized charcoal (215 kg of PCI and

35 kg of PCH) and Scenario 3: injections of 150 kg of pulverized coal and 100 kg of pulverized charcoal. For all cases the oxygen enrichment is adjusted to maintain the thermal condition of the lower part of the blast furnace which guarantee smooth operation compatible with the base case, which guarantee feasible operation procedure. Fig. 2 shows the gas flow patterns and temperature distributions compared with the base case. As can be observed, in Fig. 2(b) the temperature of the lower part of the reactor decreased; thus, higher amount of oxygen was used for the Scenarios 2 and 3 (see Table 2). Thus, it was possible to restore the temperature pattern of the lower part of the furnace for the 250 kg/thm injection cases, as can be observed in Fig. 2(c) and (d), respectively. The solid motion and cohesive zone shape are important parameters for assuring feasible operation conditions. Thus, Fig. 3(a)–(d) shows the descending solid pattern and cohesive zone shapes for the scenarios considered. As can be pointed out as the simultaneous injection was increased the cohesive zone became thicker. This behavior is attributed to the increase of the heat transfer in this region due to the increase in the gas velocity, since the thermophysical and softening–melting properties of the burden materials were maintained. Finally, the liquid flowing behavior in the dropping zone for the scenarios simulated are shown in Fig. 4(a)–(d). As observed, the liquids start to melt down and at the earlier stages move together with the coke bed, and thus, as temperature increases the liquid drops and the velocity increases. For all analyzed cases the liquid pattern was similar; however, as the productivity increased higher amounts of liquid were produced and hence interacting with the gas flow slightly moved away from the raceway zone. Therefore, for all cases considered the simulations indicated that is possible stable operations with higher productivity, oxygen enrichment and simultaneously injection rates of pulverized coal and charcoal.

4. Conclusions

In this study a six-phase mathematical model of the blast furnace has been presented, which can simulate the blast furnace operation under simultaneous injection of pulverized coal and charcoal. The model considers multiphase interactions for momentum, energy and chemical species coupled with the rates of chemical reactions. The model results were compared with actual blast furnace data and new operation techniques of higher simultaneous injection of pulverized coal and charcoal were studied. The model results indicated that further decrease in coke consumption in the blast furnace could be possible by using combined injections of 150 kg of pulverized coal and 100 kg/thm of pulverized charcoal. Therefore, the most significant contribution of this study is to determine the set of operational parameters compatible with the actual blast furnace process for trials which guarantee that inner phenomena usually difficult and expensive to monitor such as materials flows and heat transfer.

Conflicts of Interest

The authors declare no conflicts of interest.

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