MODELING THE MINI BLAST FURNACE PROCESS BASED ON SELF-REDUCING AGGLOMERATES [1]

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Abstract

The blast furnace process is the main supplier of hot metal in the steel industry. This process is massive user of carbon source materials as fuel and reducing agent. Recently the development of self-agglomerates has open the possibility of its direct use in mini blast furnace. This investigation aims to numerically simulate a mini blast furnace process operating with self-reducing agglomerates with low slag rate and high rates of pulverized biomass combined with oxygen injection and small coke as solid fuels. The model describes the mini blast furnace process as a counter current reactor of five phases interacting with one another. The solid phase considers small sinter, self-reducing pellets and briquettes as iron bearing materials and small coke as solid fuel charged from the top. The modeling is based on transport equations of momentum, energy and chemical species of each phase and the chemical reactions are modeled by semi-empirical equations. Model results are presented for global parameters and spatial distributions for temperature and composition for solid and gas phases. Smooth operational conditions were obtained for about 20% of self-reducing pellets combined with small sinter and coke in the burden materials. In addition, up to 100 kg/t of pulverized biomass could be injected in the mini blast furnace tuyeres

Key words: Multiphase model; Sintering; Biomasses.

MODELO DO MINI ALTO-FORNO BASEADO EM CARGA AUTO-REDUTORA [1]

Resumo

O processo tradicional do alto-forno é o principal supridor de metal liquido para a indústria do aço. Este processo faz uso intensivo de fontes de carbono para atuar como combustível e agente redutor. Recentemente com o desenvolvimento de aglomerados auto-redutores abriu-se a possibilidade do seu uso em mini altos-fornos. Este estudo visa simular numericamente o processo do mini alto-forno operando com baixo volume de escória e altas taxas de injeção de carvão vegetal pulverizado combinado com enriquecimento de oxigênio e small coque. O modelo é baseado em equações de transporte de momentum, energia e espécies químicas. Resultados do modelo são apresentados em termos de parâmetros globais e distribuições espaciais no interior do reator. Resultados de simulação indicaram que é possível operar de forma estável com 20% de carga auto-redutora combinado com 100 kg/t de carvão vegetal pulverizado.

Palavras-chave: Modelo multifásico; Mini alto-forno; carga auto-redutora.

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1 INTRODUCTION

The common use of the mini blast furnace process is to produce hot metal based on charcoal although depending on availability and price of the fuel could be profitable the substitution of the granular charcoal by small coke. Due to the land characteristics, Brazil is one of the few countries in the world to keep mini-blast furnaces based on the charcoal as reducing agent. This industry produces pig iron and steel of high quality because of the low level of impurity of the fuel. From the point of view of the CO_2 emission, this industry has a very positive impact because it substitutes the coke used as reducing agent by charcoal, a renewable source of energy. The use of charcoal reduces total CO_2 emission since it represents a renewable source of energy by using cultivation of eucalyptus which releases the oxygen to the environment representing a closed cycle of carbon within a period of approximated 6 years. Another notable advantage for the mini blast furnace technology is its ability for controlling the hot metal supply in the steel plant, since it is very flexible with regard to the production rate. Brazil has been developed the technology of cultivation the eucalyptus and detains a solid background in this field by massive investments on genetic improvement of the tree species and, in addition, has excellent knowledge of the operation of the mini blast furnace based on charcoal, giving a great opportunity for maintain a competitive industry when environmental restrictions become even more severe. Therefore the direct use of charcoal associated with the florets renewing is a promising technique that is currently used in the mini blast furnace, which can even release oxygen to the atmosphere. In addition, the kinetics of the charcoal is faster than the pulverized coal, which allows the use of high rates of injection through the tuyeres and minimizes the unburned coal. However, the solution loss reaction takes place at lower temperature than coke and the degradation of the granular charcoal is of special concern. Also, the use of charcoal allows the production of hot metal with very low level of impurities, which is an advantage for the subsequent refining operations. Thus, in near future, when environmental restrictions become severe, only environmentally cleaner processes associated with recycling industries would be competitive. The compact blast furnace process is an improved reactor which takes the advantages of the large blast furnace technology based on stave cooling and prepared raw materials. In order to attain small solid residence time the reducibility of the iron bearing materials is enhanced. Aiming at improving the productivity and lowering the fuel consumption this investigation is purposing high oxygen enrichment and direct use of self-reducing pellets in the solids charged from the top. These new operational conditions are expected to drastically modify the reactor performance. However, self-reducing agglomerates usually suffer high degradation and fines are generated in the shaft region. To overcome these phenomena small sinter and small coke is charged and the self-reducing agglomerates are charged in the same layer of sinter, as the result, the solid residence time in the shaft region is reduced and degradation is minored with possible increase of productivity.

2 METHODOLOGY

The methodology applied in this work conjugate numerical simulations of actual mini blast furnace operation and extension of the model to investigate new technologies which characterizes the flex fuel furnace where is possible with minor adjustment operates the compact blast furnace with high productivity in both conditions, small coke and granular charcoal. With regarding to pulverized coal, also biomass and coal can be used. In this investigation, the pulverized charcoal was chosen. Figure 1 shows a schematic view of the compact furnace and the numerical mesh of finite control volumes used in the simulations.

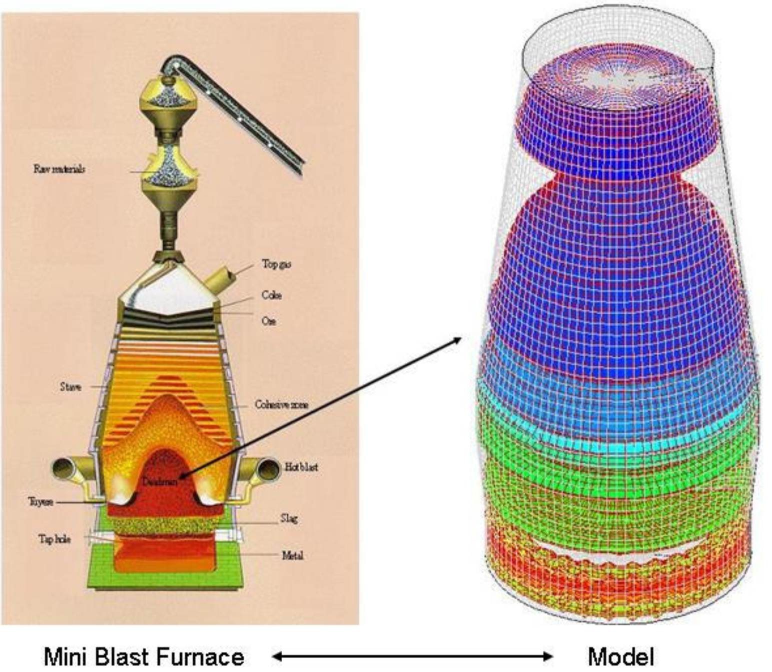


Figure 1 Mini blast furnace inner image and model domain

2.1. Model concepts

In this section, major features of the mathematical model are outlined. The mathematical model consists of a set of strongly coupled transport equations to describe the motion, energy transfer, chemical species and phase transformations. In this formulation five phases are considered. The gas phase is composed of the blast injection at the tuyeres and the gas generated by chemical reactions, namely, combustion and gasification of charcoal, reduction by hydrogen and carbon monoxide of the iron bearing materials charged from the reactor throat. The solid charged from the furnace top is the second phase. The solid is composed of alternated layers of granular charcoal, sinter and fluxes. For the charcoal blast furnace the sinter has special properties in order to adjust the slag basicity which plays an important role in the lower part of the reactor. The third phase is the hot metal, mainly composed of liquid iron, dissolved carbon, silicon, manganese, phosphorus, sulfur and small quantities of impurities. The liquid metal is formed in the cohesive zone where the reduced iron and wustite melts together with the primary slag resulted from the gangue and additives of the sinter charged. The slag and hot metal has quite different properties, such as density, viscosity, thermal conductivity. The slag and hot metal are separated by gravity when flow through the packed bed. The region where these phenomena take place is termed dropping zone and the dynamics of these two liquids in this zone play important role on the permeability to the gas phase, which in turn, determines the production rate of the furnace, since the production rate is function of the amount of oxygen injected through the tuyeres. Thus, a strict control of the liquid flow pattern within the blast furnace determines smooth operation and high productivity. Several attempts have been made to model these phenomena in the blast furnace process. Among them Yagi et al[1], Austin et al[2,3] and Castro et al[4-7]. The model developed by the authors[4] was originally applied to coke based blast furnace. In this work, this model is extended to the charcoal blast furnace and also to consider self-reducing agglomerates. The essence of the model, however, is the same despite of the rate equations for the reactions evolving the charcoal and self-agglomerates being quite different. Therefore, this model maintains the main features of previous models and adds new ones to consider new raw materials and related chemical reactions with correspondent rate equations.

2.2. Transport equations

The model is based on the multiphase principle where each phase interacts with one another exchanging momentum energy and mass due to chemical reactions and phase transformations. In this investigation five phases are considered and the interactions are determined by semi-empirical correlations. Figure 2 presents the phases and interactions considered in this model. The conservation equations for all phases are presented in eq. 1-5.

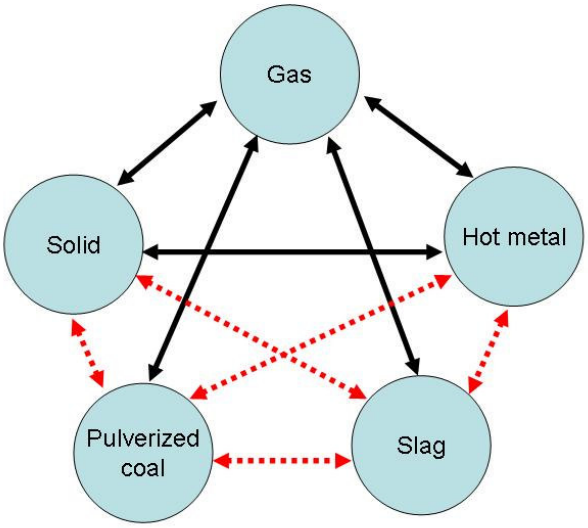


Figure 2 Five phase model applied to mini blast furnace with momentum, energy and chemical species exchanges

Momentum equations for gas and solid phases (continuous phases):

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

Momentum equations for pig iron, slag, pulverized coal and charcoal phases (discontinuous phases):

$$\frac{\partial\left(\rho_i \varepsilon_i u_j\right)}{\partial t} + div\left(\rho_i \varepsilon_i \vec{U}_i\, u_j\right) = div\left[\varepsilon_i\, \mu_i grad\,\left(u_j\right)\right] - F_i^k \tag{2}$$

Continuity:

$$\frac{\partial\left(\rho_i \varepsilon_i\right)}{\partial t} + div\left(\rho_i \varepsilon_i \vec{U}_i\right) = \sum_{l=1}^{nreacts} R_l \tag{3}$$

Energy:

$$\frac{\partial\left(\rho_i \varepsilon_i h_i\right)}{\partial t} + div\left(\rho_i \varepsilon_i \vec{U}_i\, h_i\right) = div\left[\varepsilon_i\, grad\,\left(h_i\right)\right] - \sum_{l=1}^{l=nreacts} R_l \Delta h_l + E_i^k \tag{4}$$

Chemical species:

$$\frac{\partial\left(\rho_i \varepsilon_i \phi_{i,ispeci}\right)}{\partial t} + div\left(\rho_i \varepsilon_i \vec{U}_i\, \phi_{i,ispeci}\right) = div\left[\varepsilon_i\, D_{ispeci}\; grad\,\left(\phi_{i,ispeci}\right)\right] + \sum_{l=1}^{l=nreacts} M_{ispeci} R_l \tag{5}$$

And the volume restriction gives:

$$\sum_{i=1}^{i=nphases} \varepsilon_i = 1 \tag{6}$$

The rates of momentum, energy and mass transfer are modeled by semi-empirical relations reported by Yagi[1], Austin et al[2,3] , Castro et al[4-7]. In table 2 is listed the chemical species of each phase used in this model.

Table 1 Variables and symbols used in the model

D	Diffusion coeficient (m2/s)	*i*	Index indicator of phases
ε	Phase volume fraction (m3/m3)	*j*	Index indicator of velocity component
M	Molecular weight (kg/kmol)	*k*	Index indicator of phases
P	Phase pressure(Pa)	*l*	Index indicator of chemical reaction
R	Reaction rates (kmol/s)	*ispeci*	Index indicator of chemical species
ρ	Phase density (kg/m3)	*nphase*	Total number of phases

Table 2 Phases and chemical species considered in the model for charcoal mini blast furnace

Phases	Chemical species (ϕ_i)	
Gas	CO, CO_2, O_2, H_2, H_2O, N_2, SiO, SO, SO_2	
Solids	ore	Fe_2O_3, Fe_3O_4, FeO, Fe, CaO, Al_2O_3, MgO, SiO_2, H_2O, gangue
	Small sinter	Fe_2O_3, Fe_3O_4, FeO, Fe, CaO, Al_2O_3, MgO, SiO_2, H_2O, gangue
	pellets	Fe_2O_3, Fe_3O_4, FeO, Fe, CaO, Al_2O_3, MgO, SiO_2, H_2O, gangue
	Granular charcoal	C, volatiles, SiC, SiO_2, Al_2O_3, CaO, MgO, H_2O, S, gangue
	Granular small coke	C, SiC, SiO_2, Al_2O_3, CaO, MgO, H_2O, S, gangue
	Self-reducing pellets	C, volatiles, SiC, Fe_2O_3, Fe_3O_4, FeO, Fe, CaO, Al_2O_3, MgO, SiO_2, H_2O, gangue
Pig iron	Fe, C, Si, S, P	
Slag	FeO, SiO_2, Al_2O_3, CaO, MgO,gangue	
Pulverized Charcoal	C, Volatiles, SiC, SiO_2, Al_2O_3, CaO, MgO, S, FeS, $P(P_2O_5)$, $K(K_2O)$, gangue	

Note: including momentum and continuity equations for each phase it comprises a set of 119 partial differential equations.

The chemical reactions and phase transformations are modeled based on semi empirical rate equations previously published by the authors(1-8). Additional chemical reactions were incorporated in the model to account for the biomasses and self-reducing agglomerates considered in this version of the model.

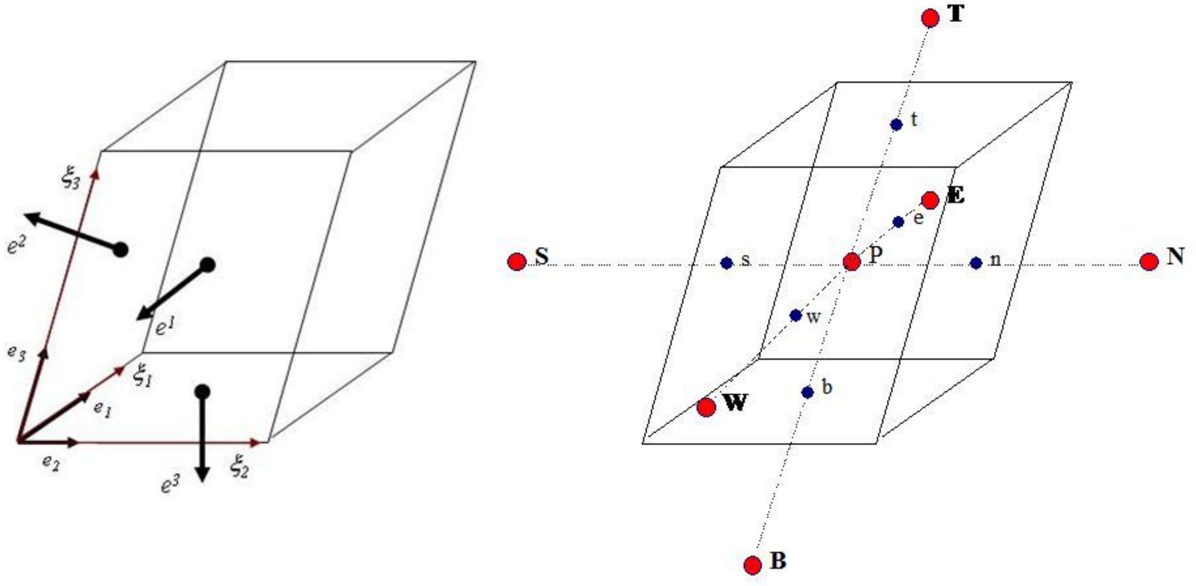
2.5. Numerical features

The model equations described above are discretised based on the Finite Volume Method (FVM) where the coupling of velocity and pressure field is done by applying the simple algorithm with staggered covariant velocity components located on the face of the finite volumes. The source terms were linearized and the resulting algebraic equations were iteratively solved based on tri-diagonal matrix line by line method(ADI). A computational code based on Fortran 90 was implemented and the computational domain was divided into 7x25x60 control volumes. Figure 3 shows the local coordinate system and computational molecule for the finite volume integration of the differential equations. In the finite volume method the general transport equation is integrated over the finite control volume with the volumetric fluxes calculated over the surfaces based on the Gauss theorem with resulting algebraic equations are presented in compact form, eq. (18), where the coefficients accounts for the information carried by the neighbor volumes and estimated by the power law scheme.

$$\int_{\delta t}\int_{\delta V}\frac{\partial(\rho\varepsilon\phi)}{\partial t}dvdt+\int_{\delta t}\int_{\delta V}\left[div\left(\rho\varepsilon\vec{U}\phi-\varepsilon\Gamma_{\phi}grad\ (\phi)\right)\right]dvdt=\int_{\delta t}\int_{\delta V}S_{\phi}dvdt \tag{12}$$

$$\int_{\delta t}\int_{\delta V}\frac{\partial(\rho\varepsilon\phi)}{\partial t}dvdt\approx J\,\frac{\left(\rho\varepsilon\phi_{P}-\rho^{0}\varepsilon^{0}\phi_{P}^{0}\right)}{\Delta t} \tag{13}$$

$$\int_{\delta t}\int_{\delta V}\left[div\left(\rho\varepsilon\vec{U}\phi - \varepsilon\Gamma_{\phi}\, grad\left(\phi\right)\right)\right] dvdt \approx F.A\rangle_{e} - F.A\rangle_{w} + F.A\rangle_{n} - F.A\rangle_{s} + F.A\rangle_{t} - F.A\rangle_{b} \tag{14}$$



a) Local coordinate system

b) Computational molecule of FVM

Figure 3 Local coordinate system and computational molecule used to discretise the domain into finite volumes

$$\int_{\delta t}\int_{\delta V} S_{\phi}\, dvdt \approx S_{C} + S_{P}\phi_{P} \tag{15}$$

$$F.A\rangle_{e} = \int_{A_e} F.dA = \left(\rho\varepsilon\vec{U}.A^{(1)}\phi - \varepsilon\Gamma A^{(1)}.\nabla\phi\right)\Big\rangle_{A_e} = F^{(1)}\rangle_{e} \tag{16}$$

$$F^{(1)}\rangle_{e} = \left[\rho\varepsilon U^{1}\phi - \varepsilon\Gamma\left(G^{11}\frac{\partial\phi}{\partial\xi^{1}} + G^{12}\frac{\partial\phi}{\partial\xi^{2}} + G^{13}\frac{\partial\phi}{\partial\xi^{3}}\right)\right]\Bigg\rangle_{e} \tag{17}$$

$$a_{P}\phi_{P} = a_{W}\phi_{W} + a_{E}\phi_{E} + a_{B}\phi_{B} + a_{T}\phi_{T} + a_{S}\phi_{S} + a_{N}\phi_{N} + b \tag{18}$$

$$a_{P} = a_{W} + a_{E} + a_{B} + a_{T} + a_{S} + a_{N} + a_{P}^{0} - S_{P} \tag{19}$$

$$b = b_{NO} + S_C + a_P^0 \phi^0 \tag{20}$$

$$b_{NO} = \left[\Gamma G^{12} \frac{\partial \phi}{\partial \xi^2} + \Gamma G^{13} \frac{\partial \phi}{\partial \xi^3} \right]_w^e + \left[\Gamma G^{21} \frac{\partial \phi}{\partial \xi^1} + \Gamma G^{23} \frac{\partial \phi}{\partial \xi^3} \right]_s^n + \left[\Gamma G^{31} \frac{\partial \phi}{\partial \xi^1} + \Gamma G^{32} \frac{\partial \phi}{\partial \xi^2} \right]_b^t \tag{21}$$

3 RESULTS AND DISCUSSION

In this section, new technological trends for the mini blast furnace process were carried out. The model was applied to simulate 10 possible operations conditions. The operations conditions were classified into two groups: The first one is a coke based operation and the second one is a charcoal based operation. For both groups increasing self-reducing agglomerates were charged from the top and finally self-agglomerates were combined with standard pulverized charcoal injection. Brazil has experienced both, coke and charcoal based operations, however general revamp of the reactor has been demanded due to quite different inner conditions regarding to refractory concerns and cooling conditions. These investigation aims to determine intermediate conditions which attends both and using modern technologies of refractory and stave coolers overcome the operation difficulties of flexible fuel utilization. In table 3 the operational parameters found for each of the simulate cases are shown. The productivity and oxygen enrichment of the new cases increased when compared with the base cases of coke and charcoal. For all cases the granular reducing/fuel agent is decreased due to the replacement of the carbon of the self-reducing agglomerates. With regard to environmental concerns, the specific sinter consumption of the cases where pulverized coal injection and self-agglomerates were used decreased considered. This is an important issue because the sinter plant is considered as the most pollutant unit operation of the steel works. Therefore, additional benefits could be obtained with these practices, in addition to granular fuel reductions and production increases. The simulation results were obtained by iterative procedure targeting similar pattern of shaft temperature in order to assure reducing conditions in the upper part of the furnace. Figure 4 shows temperature distributions of coke and charcoal based operation which corresponds to actual operation conditions of industrial scale furnace. These cases were validated with industrial data of the global parameters such as silicon content, productivity, top gas analysis and top gas distribution temperatures. As can be observed, similar pattern were predicted although the production rhythm is quite different, demonstrating feasible operations. One of the most concern of the furnace operators when self-agglomerates is charged is the alkalis compounds that could be formed and circulate within the furnace accumulating and modifying the melting down properties of the iron bearing material near the cohesive zone. To inspect the formation of these materials the cohesive zone position, sodium and potassium are plotted in figures 5, 6 and 7, respectively. As can be observed the most restrictive conditions for the operation was observed for the combined operation of high self-reducing agglomerates and pulverized coal injection due to strong effect of temperature and gas flow pattern in the concentration of these chemical species which evaporates at high temperatures and condensation occurs in low temperatures. However the model predicted the extension and location of these zones indicating safety operations, as shown in figures 6 and 7.

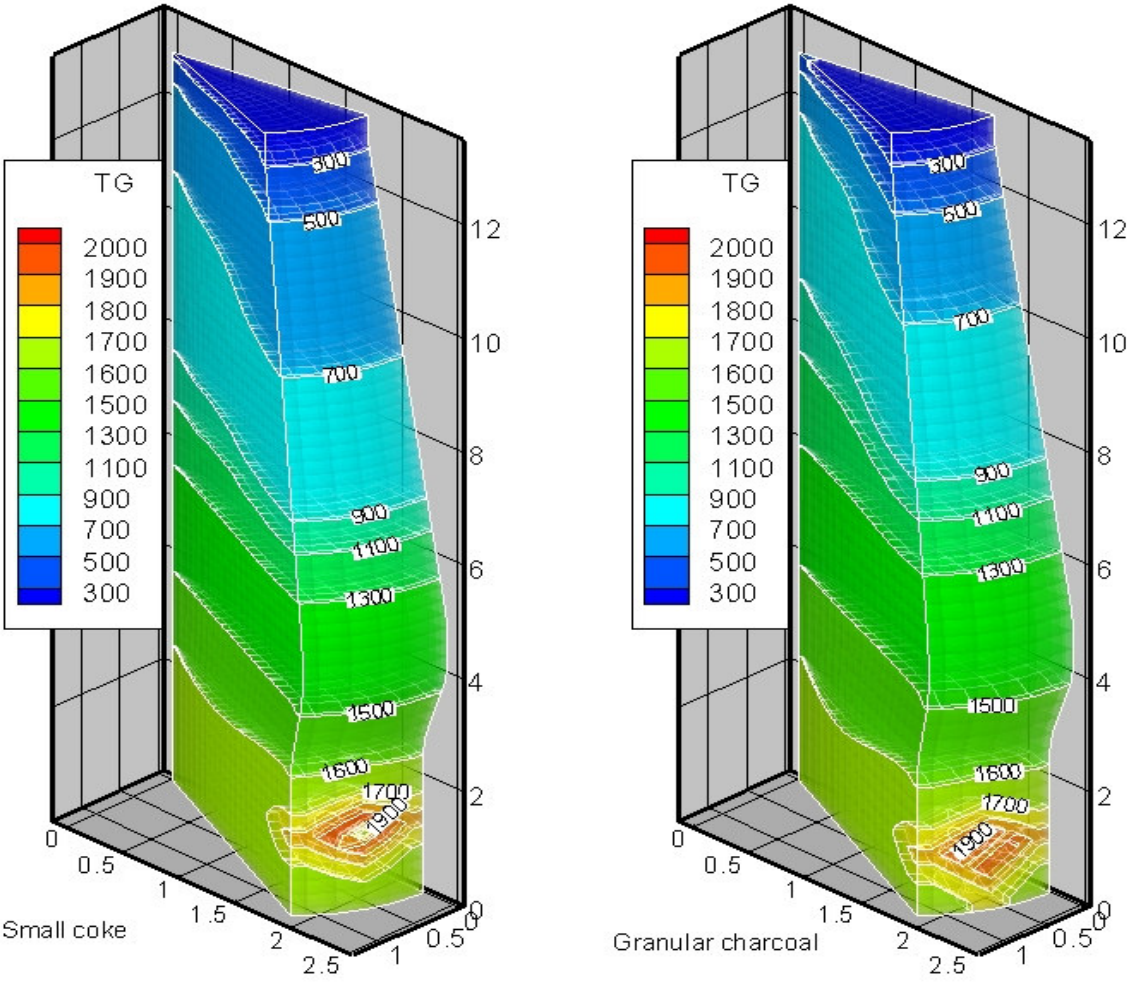


Figure 4 Comparisons of inner temperature distributions for small coke and granular charcoal operations in the mini blast furnace

Table 3 Operational parameters predicted by the mini blast furnace model

Coke based mini blast furnace						Granular charcoal based mini blast furnace				
	Base	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Base**	**Case 1**	**Case 2**	**Case 3**	**Case 4**
PCI[kg/t]	-	-	99.1	99.1	99.1	-	-	98.95	99.02	99.03
Self-reducing agglomerates [kg/t]	-	334.2	-	81.7	334.7	-	329.3	-	80.6	330.9
Granular reducing agent [kg/t]	571.3	483.9	475.7	449.1	375.1	702.3	582.6	585.9	568.9	490.6
Sinter [kg/t]	1602.9	1322.9	1601.8	1534.3	1324.5	1575.8	1303.2	1580.5	1513.9	1307.8
Fuel rate [kg/t]	572.3	574.8	574.9	570.4	565.2	702.3	672.1	684.9	689.9	679.6
Carbon rate[kg/t]	504.02	517.7	491.0	489.7	493.2	515.4	517.1	501.2	510.8	521.3
Productivity [t/m^3/dia]	1.88	1.99	2.06	2.08	2.08	1.96	2.06	2.03	2.01	2.00

Oxigen enrichment [%]	3.95	5.37	4.60	5.04	6.02	3.73	5.91	4.71	5.26	6.24
Production [t/day]	361.7	382.5	396.2	399.6	400.5	377.4	396.6	391.5	387.7	384.4
Si [%]	0.83	0.64	0.76	0.67	0.43	2.14	1.83	1.85	1.81	1.52
Slag [kg/t]	279.2	298.4	303.1	303.2	303.4	222.2	225.9	238.6	238.1	244.3
Basicity[-]	0.67	0.67	0.67	0.69	0.75	0.82	0.76	0.88	0.869	0.810
Blast [Nm^3/t]	1386.5	1386.4	1338.7	1327.1	1324.1	1405.1	1337.2	1354.5	1367.9	1379.5
Top gas [Nm^3/t]	1949.6	1946.6	1937.9	1919	1904.7	2206.6	2084.4	2152.5	2165.5	2151.0
$\frac{CO_2}{CO_2 + CO}$	0.48	0.449	0.475	0.495	0.47	0.252	0.27	0.283	0.295	0.289
Pressure drop [atm]	0.51	1.00	0.57	0.784	1.198	0.886	1.116	0.941	1.03	1.249

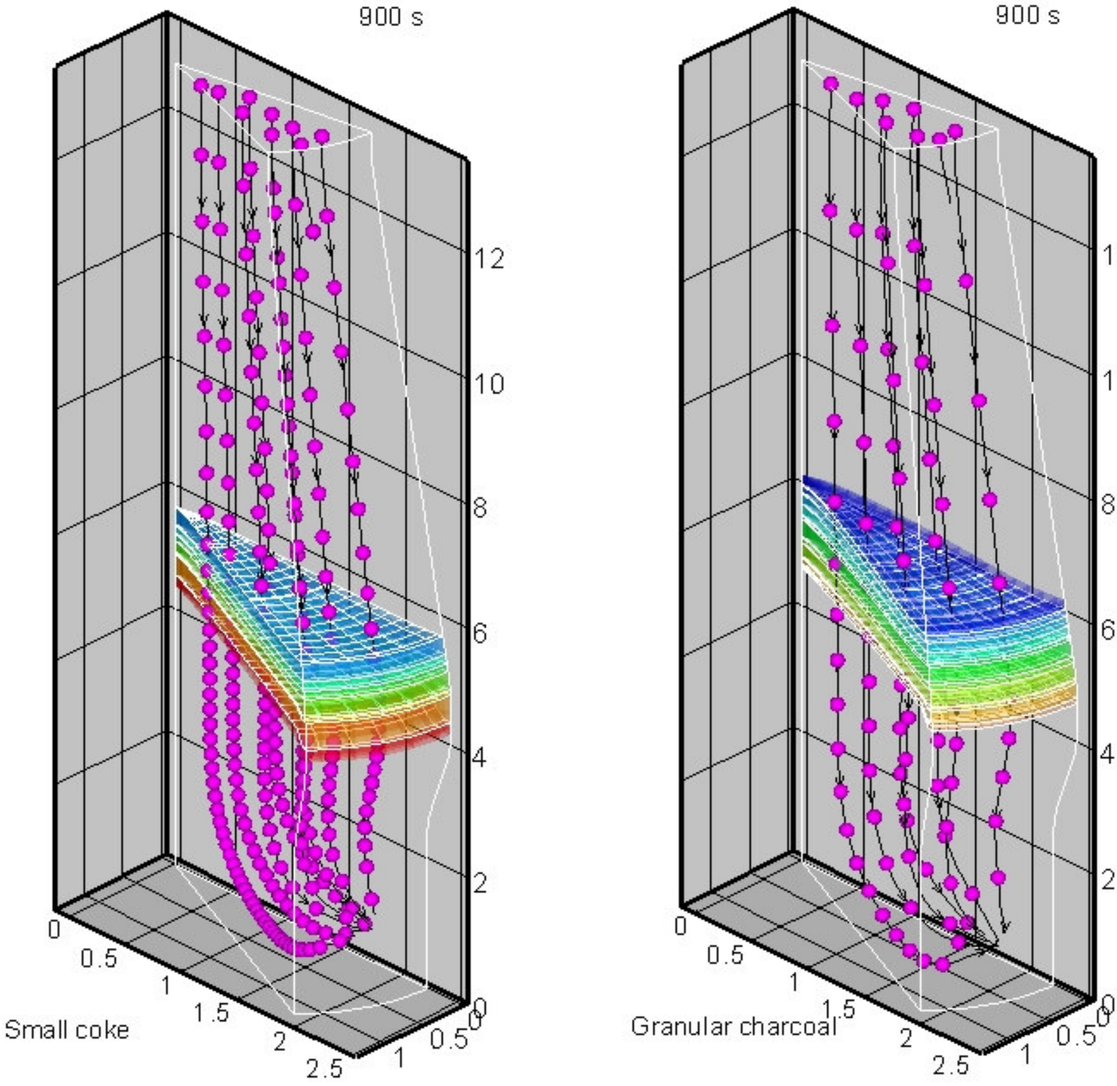


Figure 5 Computed results of solid flow and cohesive zone position for small coke and granular charcoal operations

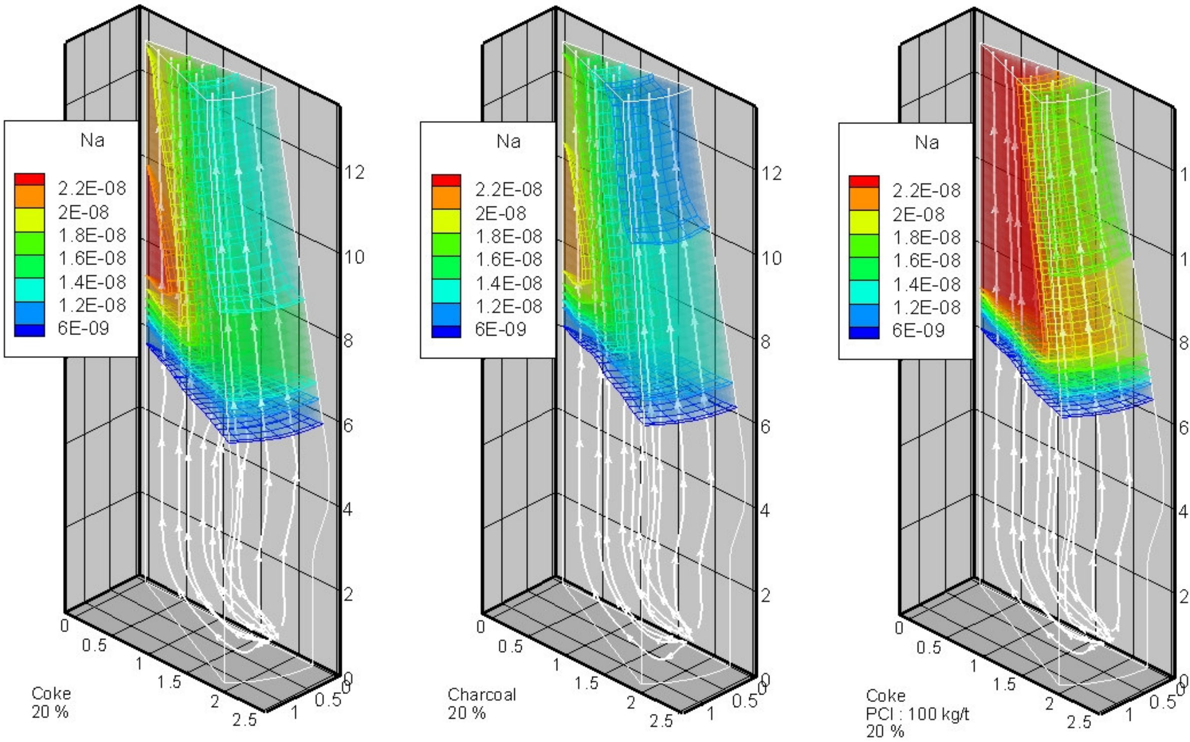


Figure 6 Predictions of sodium recirculation within the mini blast furnace using 20% of self-reducing agglomerates as metallic burden: a) small coke b) granular charcoal and c) pulverized charcoal

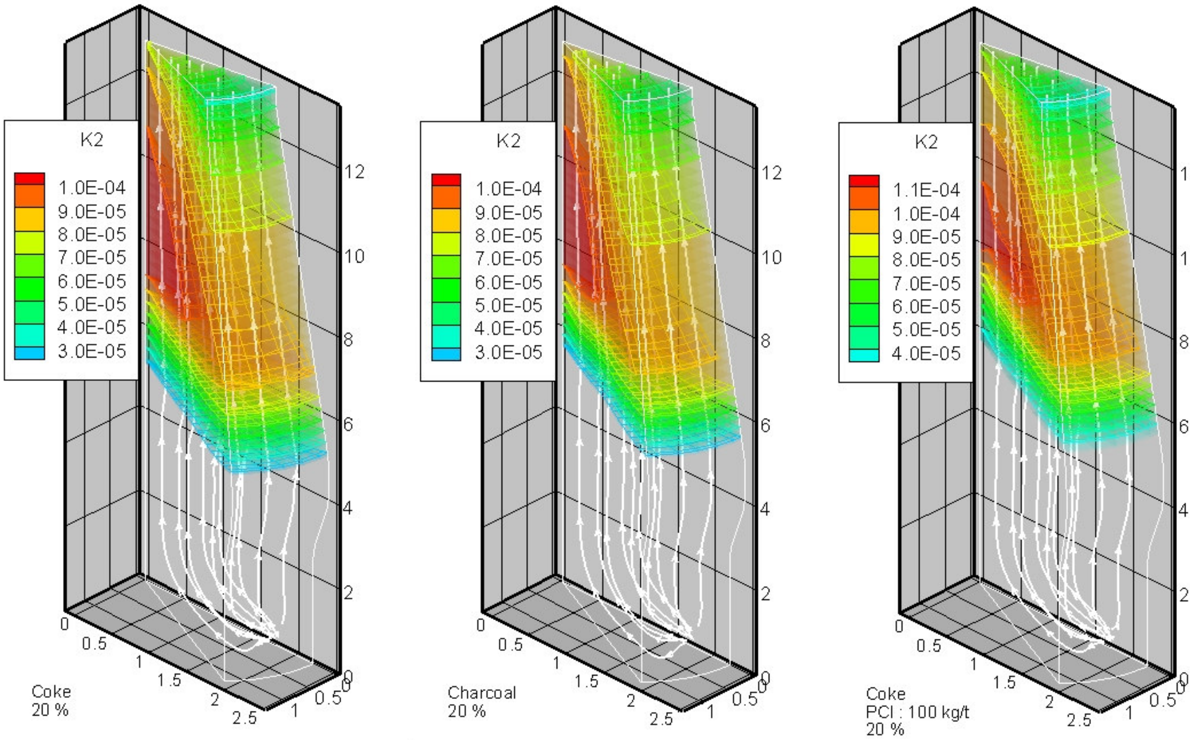


Figure 7 Predictions of potassium recirculation within the mini blast furnace using 20% of self-reducing agglomerates as metallic burden: a) small coke b) granular charcoal and c) pulverized charcoal

4 CONCLUDING REMARKS

A model capable of simulating the mini blast furnace process based on both granular coke and charcoal has been developed. The model is based on transport equations of momentum, energy and chemical species on a five phase system coexisting simultaneously within the reactor. The model was applied to investigate smooth operation compatible with techniques, charcoal and coke. New chemical species and chemical reactions were introduced to account for the behavior of self-reducing agglomerates into the iron bearing materials charged from the blast furnace top. Simulated results indicated that up to 20% of the sinter could be replaced by self-reducing agglomerates keeping smooth operation. Model predictions indicated that is possible to decrease the coke consumption from 571 kg/t to 375 kg/t by combining 20% of self-reducing agglomerates in the burden and 100kg/t of pulverized coal when coke based operations is considered. On the same hand, these combinations for charcoal based operations confirmed higher replacement and higher productivity, indicating clear advantages for the biomass based operation in both, granular and pulverized biomasses. All cases simulated presented stable thermal field in the lower part of the furnace indicating feasible and safety operations. Intermediate basicity and slag volumes were obtained which confirm the possibility of flex fuel operation with improvements of furnace design, refractory and cooling conditions in the lower part of the reactor.

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