A MULTIPHASE MODEL FOR THE MINI BLAST FURNACE PROCESS

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Abstract. *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 50% of self-reducing pellets and briquettes combined with small sinter and coke in the burden materials. In addition, up to 150 kg/t of pulverized biomass could be injected in the mini blast furnace tuyeres.*

Keywords*: mini blast furnace, modeling, multiphase, transport equations*

1. INTRODUCTION

The compact blast furnace process is a counter flow complex reactor whose main purpose is to produce pig iron. The common use of this reactor is to produce hot metal based on charcoal. Due to the land characteristics, Brazil is one of the few countries in the world to keep some 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 important 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 new eucalyptus forests which release 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 of 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 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 because the taxes will be unsupportable for the blast furnace based on coke.

In this paper a mathematical model of the charcoal mini blast furnace is presented to simulate the furnace operation with injection of pulverized charcoal and the blast enriched by oxygen. Simulations are carried out in order to compare the in-furnace response for high rates of pulverized charcoal injection. The model is based on the multi-phase theory and considers explicitly five phases (gas, lump solid, molten metal molten slag and pulverized coal and charcoal). Each phase has its own composition and properties, and reactions involving all phases are considered. 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 reduced with possible increase of productivity.

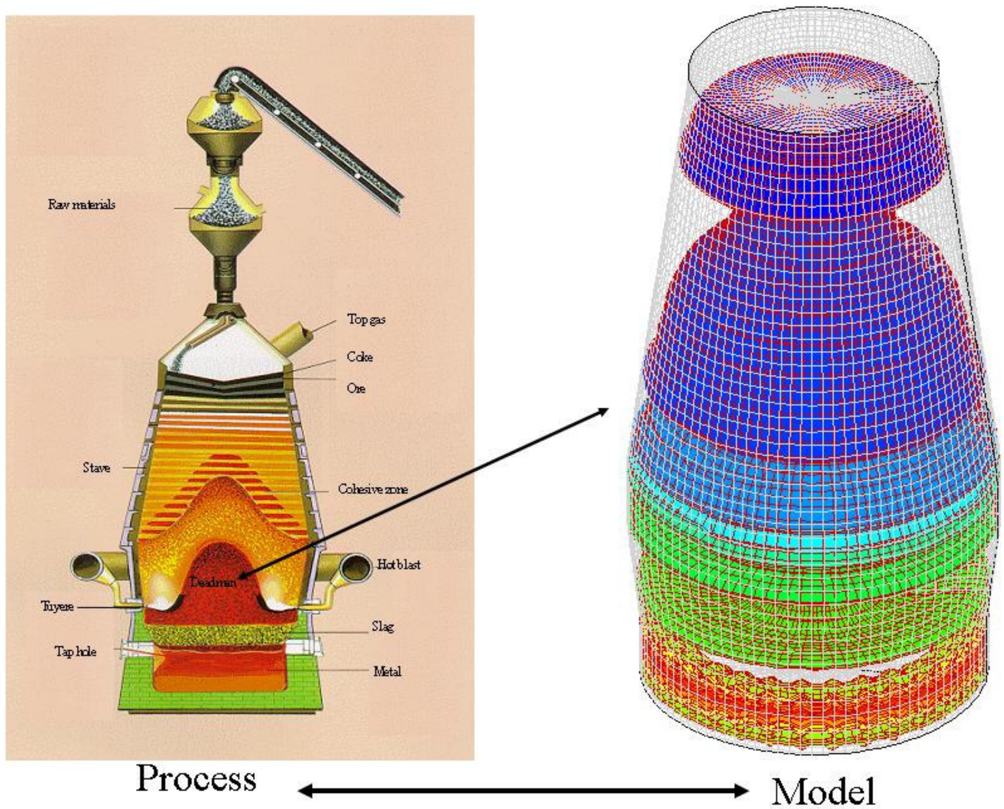

Figure 1 Inner zones and finite volume mesh generated to simulate the compact blast furnace process

2. MODELING

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 (Yagi, 1993), Austin et al(Austin et al ,1997a, Austin et al ,1997b) and Castro et al(Castro et al, 2000, Castro et al, 2001, Castro et al, 2002a, Castro et al, 2002b, Castro et al, 2002c). The model developed by the authors 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.

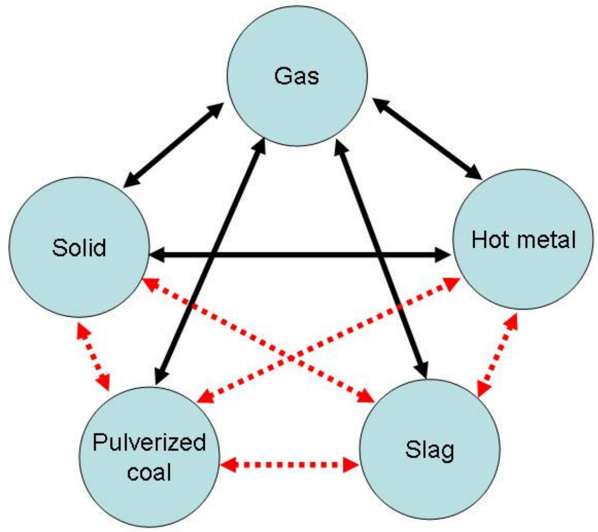

Figure 2 phase interaction of mass, momentum and energy

2.1. 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.

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

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

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

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

Continuity:

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

Energy:

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

Chemical species:

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

And the volume restriction gives:

$$\sum_{i=1}^{i=nphases} \varepsilon_i = 1 \quad (6)$$

Figure 2 shows the phases and main interaction considered in this model. As can be noticed, momentum, energy and chemical species are exchanged among the phases. The rates of transfer is modeled by semi-empirical relations and can be found elsewhere(Yagi, 1993, Austin et al ,1997a, Austin et al ,1997b, Castro et al, 2000, Castro et al , 2001, Castro et al, 2002a, Castro et al, 2002b, Castro et al, 2002c). 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 (m^2/s)	i	Index indicator of phases
ε	Phase volume fraction (m^3/m^3)	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/m^3)	*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, eq. 1

2.2. Boundary conditions

The computational domain is considered as the packed bed limited at the bottom by the slag surface and at the top by the burden surface and lateral walls. The boundary conditions applied at the walls is no momentum and mass flux. No slip condition is assumed for gas phase and coulomb attrition law is used to model the solid phase. For all chemical species no gradient are assumed while a effective heat transfer coefficient is adopt for the energy equations off all phase pondered by their volume fractions. At the top the gas phases is assumed as fully developed flow while solid inflow is modeled assuming no gradient velocity and prescribed inlet temperature.

2.3. Chemical reactions

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

2.4. Numerical procedure

In order to solve the partial differential equations stated above the Finite Volume Method based on general curvilinear coordinates with body fitted system was selected. To solve the momentum equations of continuous phases the SIMPLE algorithm is applied and discretized coefficients are determined using the power low scheme. For the discontinuous phases the momentum equations are solved coupled with the continuity equation where the incognita is the phase volume fraction. The upwind scheme is applied to discretise the continuity equations of these phases while power law is used for covariant velocities components. The algebraic equations are solved based on the the solution of a tridiagonal system combined with the line by line iterative procedure. Figure 3 shows numerical features of the implemented model. The algorithm was implemented in Fortran 90 and is an open code able to introduce new equations and sub-models.

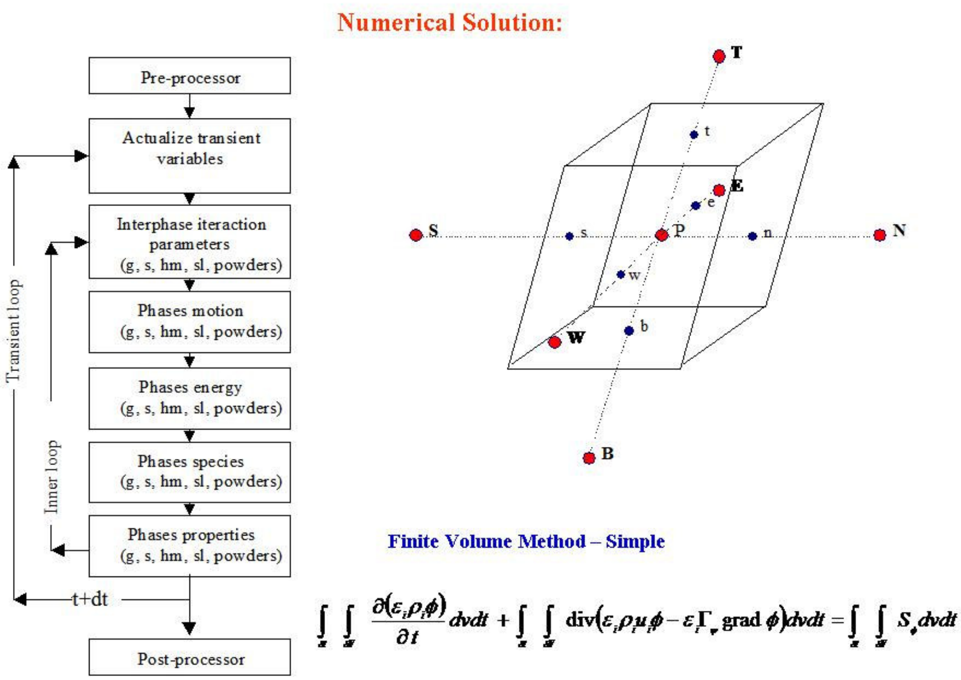

Figure 3 algorithm and computational molecule for the mini blast furnace model

3. RESULTS AND DISCUSSIONS

In order to confirm the model applicability and investigate new technological trends for the mini blast furnace process 10 possible operations conditions were simulated. The operations conditions were selected 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 coal 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, besides 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.

Table 3 Operational parameters predicted by the mini blast furnace model for all cases simulated

	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

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 can predict the extension and location of these zones and determines safety operations, as shown in figures 6 and 7.

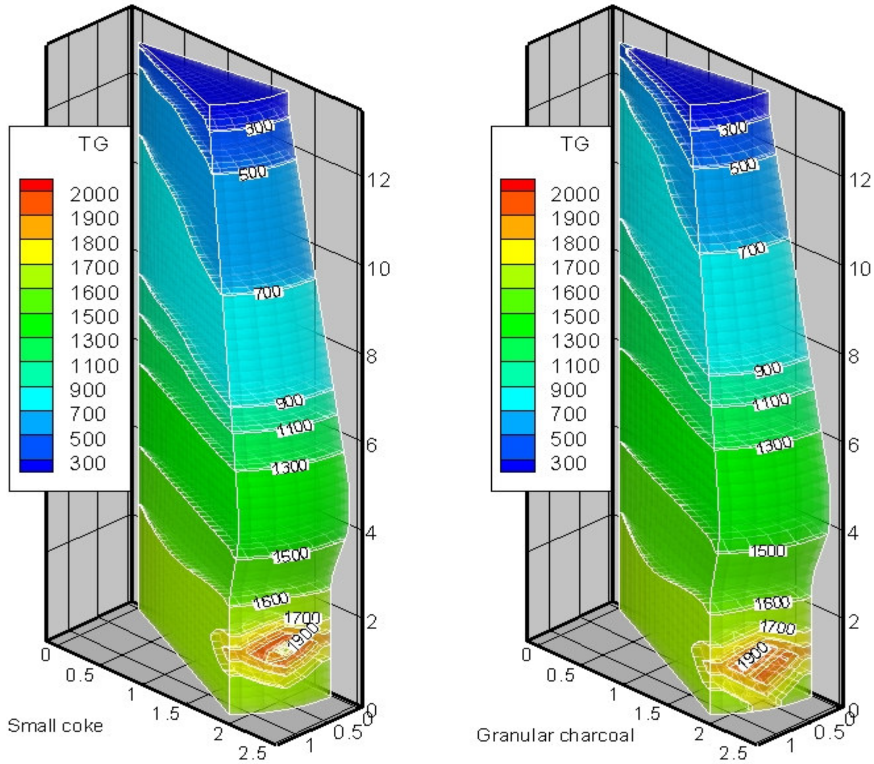

Figure 4 comparison of gas phase inner temperature distribution for mini blast furnace operation based on small coke and charcoal

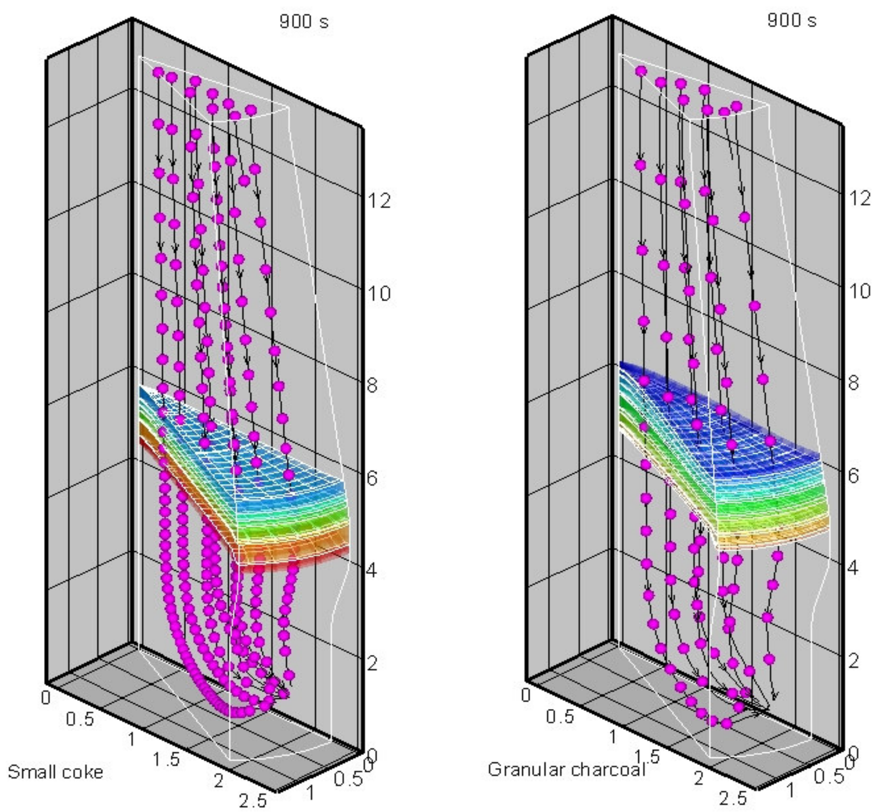

Figure 5 Comparison of solids motion and cohesive zone location for mini blast furnace operation based on small coke and charcoal

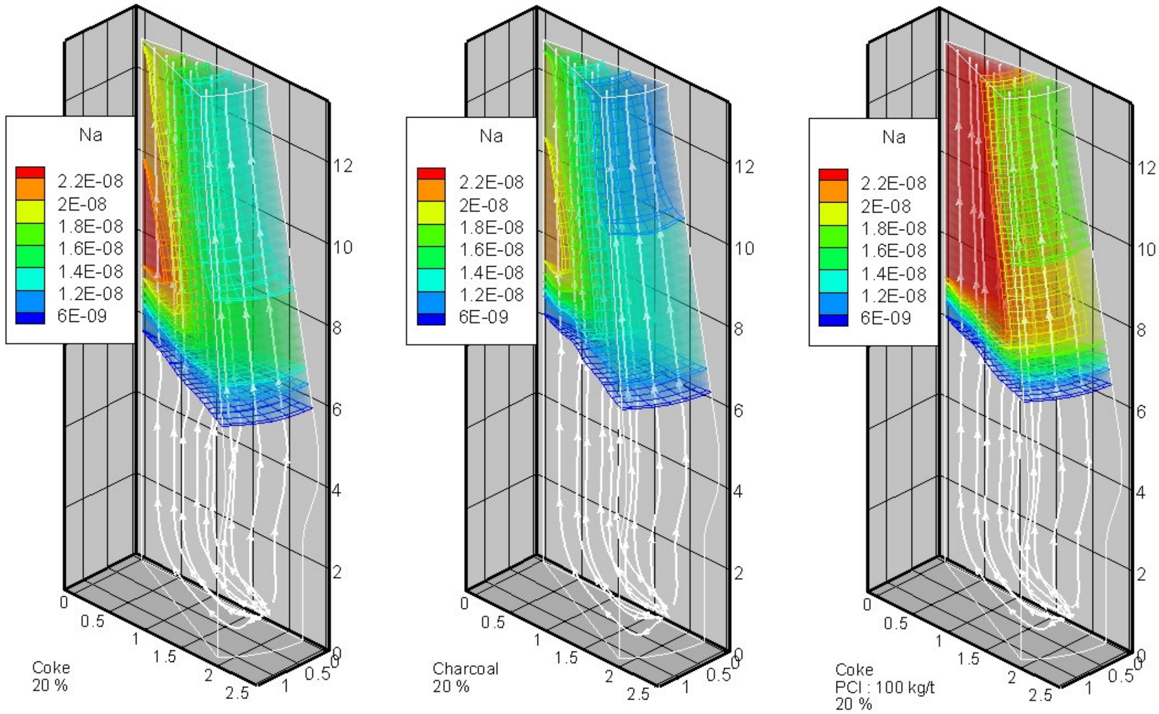

Figure 6 Comparison sodium recirculation and gas flow pattern with high amount of self-reducing agglomerates for both coke and charcoal based operations

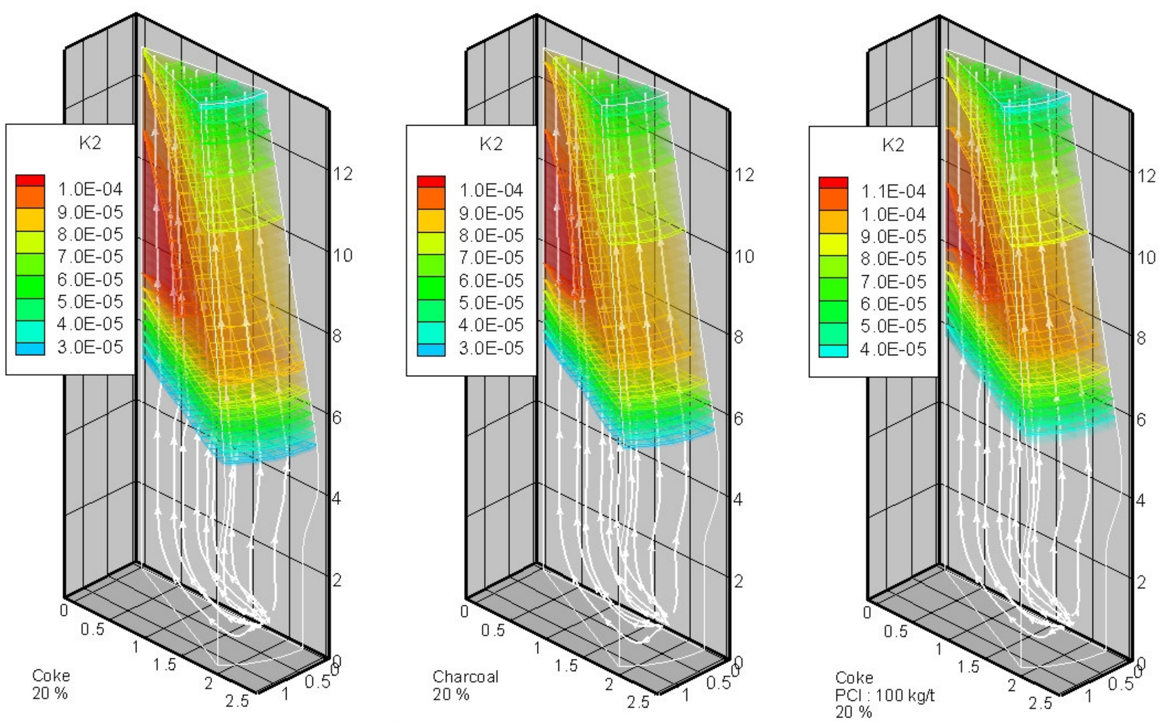

Figure 7 Potassium circulation in the furnace burden for high utilization of self-reducing agglomerates

4. CONCLUDING REMARKS

In this paper a model able to simulate the mini blast furnace based on both granular coke and charcoal was presented. 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 both techniques, charcoal and coke. New chemical species and chemical reactions were introduced enabling to analyze the introduction 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 conditions. The simulation results 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 of granular charcoal and higher productivity, indicating clear advantages for the charcoal based operation, however the biomasses have to be cultivated and the origin strictly controlled to avoid use of native forest.

5. REFERENCES

Austin, P.R., Nogami, H. and Yagi, J., 1997, "A Mathematical Model of Four Phase Motion and Heat Transfer in the Blast Furnace". ISIJ Int., Vol. **37**, pp. 458-467.

Austin, P.R., Nogami, H. and Yagi, J., 1997, "A Mathematical Model for Blast Furnace Reaction Analysis Based on the Four Fluid Model". ISIJ Int., Vol. **37**, pp. 748-755.

Castro, J.A., Nogami, H. and Yagi, J., 2000, "Transient mathematical model of blast furnace based on multi-fluid concept, with application to high PCI operation". ISIJ Int., Vol. **40** , pp. 637-646.

Castro, J.A, 2001, "A multi-dimensional transient mathematical model of the blast furnace based on the multi-fluid model". Ph.D thesis, IMRAM – Institute for multidisciplinary research for advanced materials – Tohoku University – Japan

Castro, J.A., Nogami, H. and Yagi, J., 2001, "Numerical Analysis of Multiple Injection of Pulverized Coal, Prereduced Iron Ore and Flux with Oxygen Enrichment to the Blast Furnace". ISIJ Int., Vol. **41** , pp. 18-24.

Castro, J.A., Nogami, H. and Yagi, J., 2002, "Numerical Investigation of Simultaneous Injection of Pulverized Coal and Natural Gas with Oxygen Enrichment to the Blast Furnace". ISIJ Int., Vol. **42**, pp 1203-1211.

Castro, J.A., Nogami, H. and Yagi, J., 2002, "Three-dimensional Multiphase Mathematical Modeling of the Blast Furnace Based on the Multifluid Model". ISIJ Int., Vol. **42**, pp. 44-52.

Castro, J.A., Silva, A. J., Gomes, D. E., Nogami, H. and Yagi, J., 2002, "Three Dimensional Mathematical Model of the Blast Furnace: Application to simulate the Charcoal Mini Blast Furnace". Proc. of Fourth Japan-Brazil Symposium on Dust Processing-Energy-Environment in Metallurgical Industries, eds EPUSP, São Paulo, pp 41-52.

Yagi, J., 1993, "Mathematical Modeling of the flow of four fluids in packed bed". ISIJ Int., Vol. **33**, pp. 619-639

6. ACKNOWLEDGEMENTS

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