NUMERICAL INVESTIGATION OF CO_2 RECYCLING INTO THE BLAST FURNACE COMBUSTION ZONE[1]

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Abstract

The blast furnaces process produces gas with relative high calorific value, which is commonly used in the steelmaking facilities. However, CO_2 rich gas can not be used in the process and it is desirable to minimize the emissions due to global warming effects. In this investigation, a total model of the blast furnace is used to investigate the injection of CO_2 into the tuyeres promoting water shift reaction and solution loss generating reducing gas to the process. The total blast furnace model is based on transport equations of momentum, energy and chemical species for solids, gas, hot metal, slag and pulverized phases. Four cases were selected with CO_2 recycling and blast volume together with oxygen enrichment adjustment in order to keep smooth operation. For the cases of high CO_2 injection burden distribution were changed aiming at promoting better gas flow conditions. The CO_2 injected was heated up nearly the blast temperature to minimize the thermal effect on the raceway. Simulated results indicated that productivity could be increased around 15% due to the combined effect of higher consumption via solution loss on PCI and higher reducing gas generation on the lower part of the furnace.

Key Words: Blast Furnace, Recycling CO_2, Computational simulation

INVESTIGAÇÃO NUMÉRICA DA RECIRCULAÇÃO DE CO_2 NA ZONA DE COMBUSTÃO DO ALTO FORNO[1]

Resumo

O processo do alto forno produz gás com um alto poder calorífico, que são normalmente usados para facilitar os processos industriais. Porém o gás rico em CO_2 pode não estar sendo usado no processo, e sua utilização é desejável para minimizar as emissões devido aos efeitos do CO_2 no aquecimento global. Neste trabalho, um modelo total do alto forno é utilizado para investigar a injeção destes gases ricos em CO_2 pelas ventaneiras. O modelo do alto forno é baseado na equação geral de transporte, transportando massa, momentum e energia, considerando as fases sólidas, gasosas, metal liquido, escória e finos, dentro do leito do alto forno. Quatro casos foram selecionados utilizando a recirculação de CO_2 com enriquecimento de oxigênio. Para os casos com alta taxa de injeção de CO_2 a distribuição de carga foi modificada visando promover uma melhor fluidez dos gases. O gás foi aquecido até a temperatura de sopro minimizando a perda térmica na zona de combustão. Os resultados simulados apresentaram um aumento na produtividade de 15% devido ao efeito do alto consumo de PCI via reação de solution loss na parte inferior do alto forno.

Palavras chaves: Alto forno, Recirculação de CO2, Simulação Computacional.

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1- INTRODUCTION

The blast furnace is the reactor whose main purpose is to produce the hot metal using prepared raw materials such as lump ore, sinter, pellets, coke and slagging agents. In the actual operation technique the blast furnaces uses injection of pulverized and gaseous materials into tuyeres and these new techniques have contributed to improve the furnace efficiency regarding to fuel consumption, productivity and environment. Due to environment concerns, the top gas recycling is a promising operation mode which can enhance the operation and promote low specific generation of top gas. In this investigation the CO_2 top gas recycling is addressed, where the gases from the top of the furnace is mixed with the blast gases at the tuyeres. With this technique, is expected to decrease production cost and increase furnace productivity, besides environment benefits due to decrease of CO_2 emissions [(1)].

The gas injected into the tuyeres controls the temperature of combustion zone and increase the reducing gases generated. For the cases of high CO_2 injection the burden distribution were changed aiming at promoting better gas flowing conditions and thermal exchange. The CO_2 injection is very important to control temperature in combustion zone promoting water gas shift reaction and solution loss with generation of high reducing gas volume to the shaft improving the solid reduction and allowing smaller residence time in this zone. With the combustion zone temperature control is possible an increase in PCI rate, decreasing the coke consumption and consequently fuel rate, increasing productivity.

This work uses a three-dimensional mathematical model of the blast-furnace[(2-6)] based on multiphase reactions and phase transformations, where all phases interact with one another exchanging mass, momentum and energy. Three different operational conditions were considered in the simulations. (1) Base case; real operation of the blast-furnace; (2) Case 1; enrichment 6.5% and about 10 Nm^3/t of recycling gas; (3) Case 2; enrichment 8,5% and 55 Nm^3/t (4) Case 3; enrichment 11,5% and 80 Nm^3/t and (5) case 4; enrichment 15,5% and 100 Nm^3/t

2- MODELING AND METHODOLOGY

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. 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

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 the five phases 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:

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

And the volume restriction gives:

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

Figure 1 shows the phases and main interaction considered in this model. As can be noticed, momentum, energy and chemical species are exchanged among the phases. In table 2 is listed the chemical species of each phase used in this model.

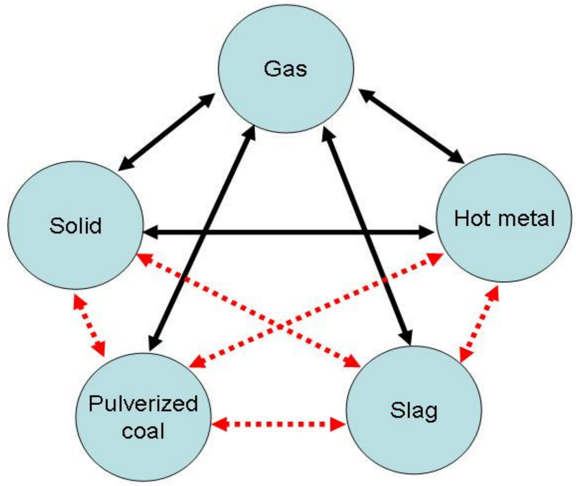


Figure 1: phase interaction of mass, momentum and energy

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

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
	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
	coke	C, SiC, SiO_2, Al_2O_3, CaO, MgO, H_2O, S, gangue
Hot Metal	Fe, C, Si, S, P, Mn	
Slag	FeO, SiO_2, Al_2O_3, CaO, MgO,gangue	
Pulverized coal	C, Volatiles, SiC, SiO_2, Al_2O_3, CaO, MgO, S, FeS, gangue	

The recirculation of the top gas of blast furnace is a promising technique that allows a series of improvements on the furnace operation such as high productivity, less specific CO_2 emissions and low silicon content. In this work the top gas is recovered, heat and injected through the tuyere mixed with blast enriched of O_2. The CO_2 is heated up until around 1250℃ to minimize the thermal effects on the raceway. In order to understand and determine feasible operations in the process a base case was selected which represents the actual operation of the furnace. Following, several trials were carried out to identify smooth operational conditions compatible with CO_2 injection. The key control parameters used were the oxygen enrichment and burden pattern. The adjustments of the blast and burden conditions were tried until get stable operation conditions, which in turn, indicate possible operations. For all cases the PCI rate was aimed at 213 kg/t and the recycling gas was heated up at the same blast temperature. The oxygen enrichment was used to minimize thermal effects in the lower part of the furnace and has the consequence of productivity increase. However, high oxygen enrichment decreased the nitrogen composition of the inner gas and heat exchanges could be deteriorated. With high CO_2 into the lower zone it is converted into CO by water shift and solution loss and the thermal replacement effect of nitrogen is minored.

3- RESULTS AND DISCUSSIONS

The main target of the simulation cases is to compare with a industrial operation. It was selected 4 cases with increasing amount of CO_2 recycling and by "trials and error" adjusting oxygen and burden distribution pattern, the stable conditions were obtained. In table 3 main operational parameters are shown. As can be observed, up to 100 Nm^3/t of CO_2 recycling was possible.

Table 3: Operational parameters

Parameters	Base	Case 1	Case 2	Case 3	Case 4
CO_2 injection(Nm^3/t)	0	11.4	56.5	78.9	103.3
O_2 enrichment (%)	5.7	6.4	8.7	11.27	15.6
Blast volume(Nm^3/min)	6149	6149	5998	5995	5965
Blast temperature (℃)	1250	1250	1250	1250	1250
PCI Injection (kg/t)	213	212.9	212.8	213	213
PCI efficiency (%)	99	92.5	100	100	100
Coke rate(kg/t)	206.2	206.5	208.6	210.7	210.2
Small coke(kg/t)	63.7	63.8	64.3	65.2	63.7
Fuel rate(kg/t)	482.2	483.3	485.7	488.9	485.7
Outlet gas					
CO_2(%)	25.2	26.5	27.9	29.1	31.2
CO(%)	18.4	18.4	22.1	24.3	27.1
H_2(%)	7.3	7.6	7.8	8.3	7.9
H_2O(%)	4.1	4.5	3.6	3.6	3.9
Temperature (℃)	198	179	183	174	151

The main target of the simulation cases is to compare with industrial operation. It was selected 4 cases with increasing amount of CO_2 recycling. The model predictions for the burden distribution pattern selected for all cases are shown in figure 2. Special mention is done in fig. 2c and d where granular coke was charged in the centre of the furnace to allow central gas flow. In Figure 2e almost uniform distribution is recovered. Figure 2f shows the size distribution of the burden materials with small segregation at the central and peripheral regions. Figure 3 shows productivity and oxygen enrichment for all cases simulated. The productivity shows clear correlation with the oxygen enrichment which is expected even without CO_2 recycling. Figure 4 shows CO_2 and outlet gas generation for analyzed cases. It is observed higher decrease of the outlet gas compared with CO_2 emission because CO_2 concentration of the outlet gas decreased as CO_2 injection increased. Figure 5 presents the consumption of carbon via solution loss reaction for granular fuels and pulverized coal injection. In both materials the consumption of carbon via this reaction increased as expected due to higher concentration of CO_2 in the gas phase in the temperature range of high reaction rates.

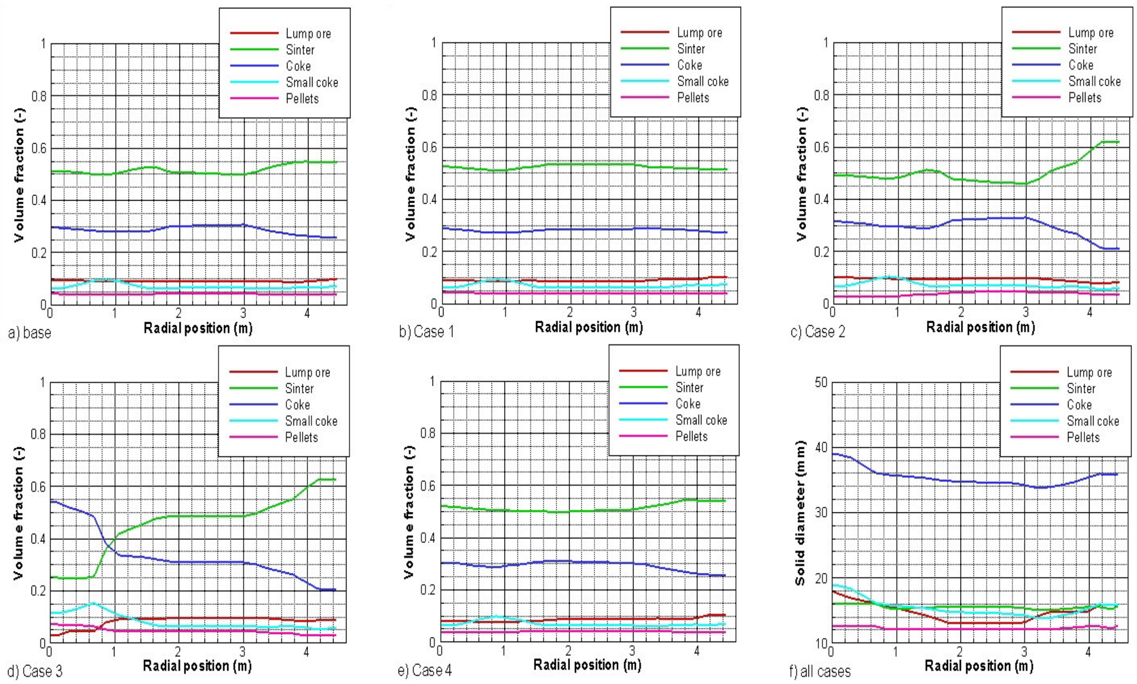
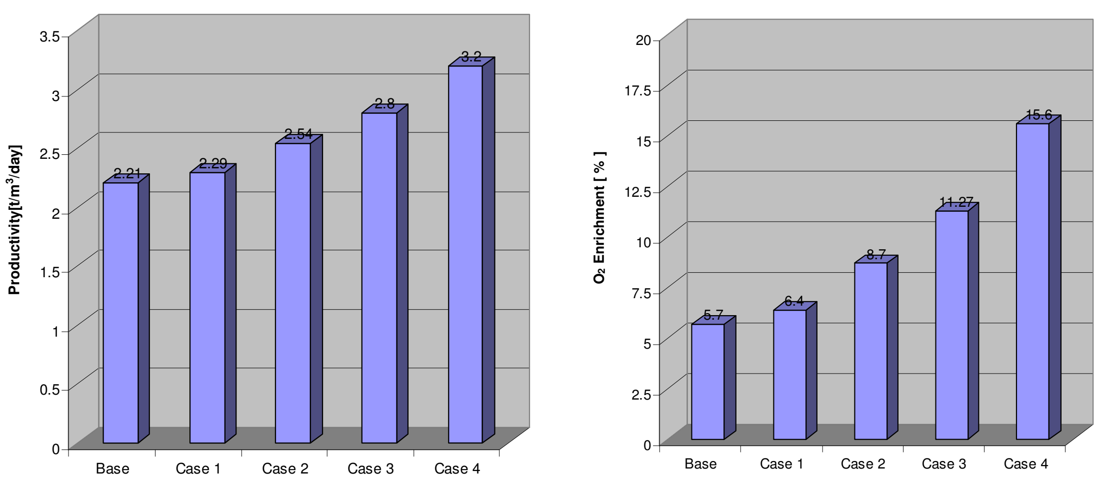


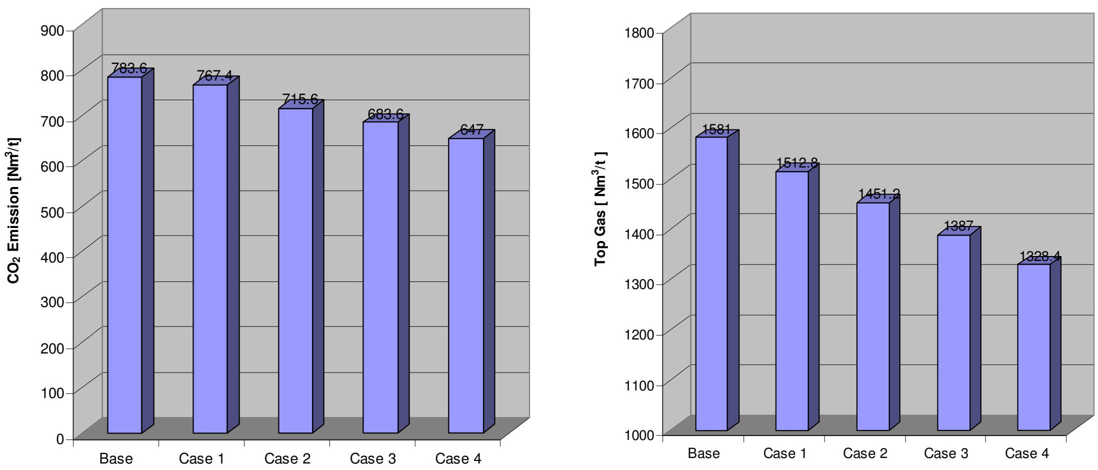
Figure 2 Burden distribution pattern predicted by the model for all cases analyzed



a) productivity

b) Oxygen enrichment

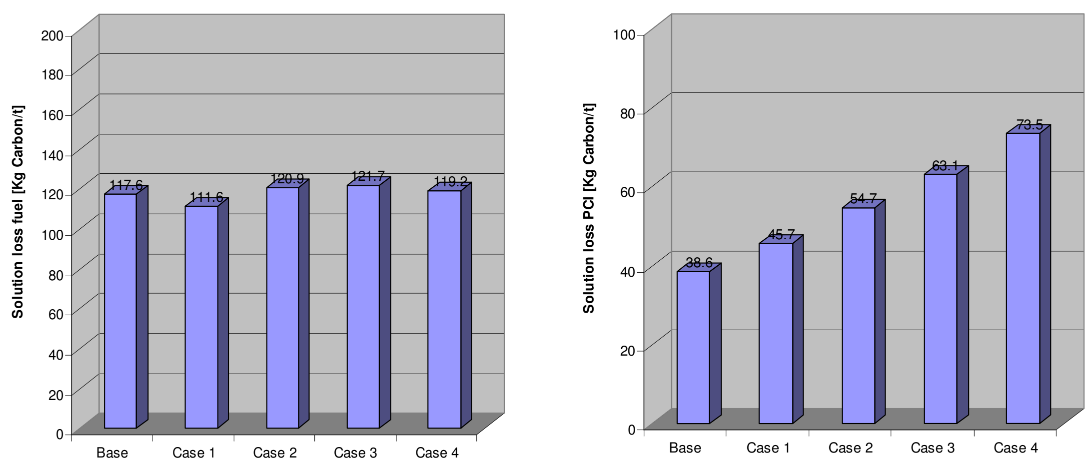
Figure 3 Operational parameters for CO_2 recycling technique



a) Specific CO_2 emissions

b) Net gas outlet

Figure 4 Outlet gas generated for CO_2 recycling cases



a) Coke + small coke

b) PCI

Figure 5 Solution loss reaction for CO_2 recycling cases

Figure 6 shows inner temperature distribution of gas phase of the blast furnace. As can be observed, the upper zone is mainly affected by the burden distribution pattern with the lower zone is strongly affected by the CO2 injection. As the injection amount was increased a cool zone is formed near the raceway which strongly affect the solid and combustion zone structure. For high injection of CO2 a “bird nest” is developed and solid flow became irregular indicating unstable operation. Therefore the model recommends safety operations for low injection rates and very unstable conditions for high injection rates, as exemplified on cases 3 and 4.

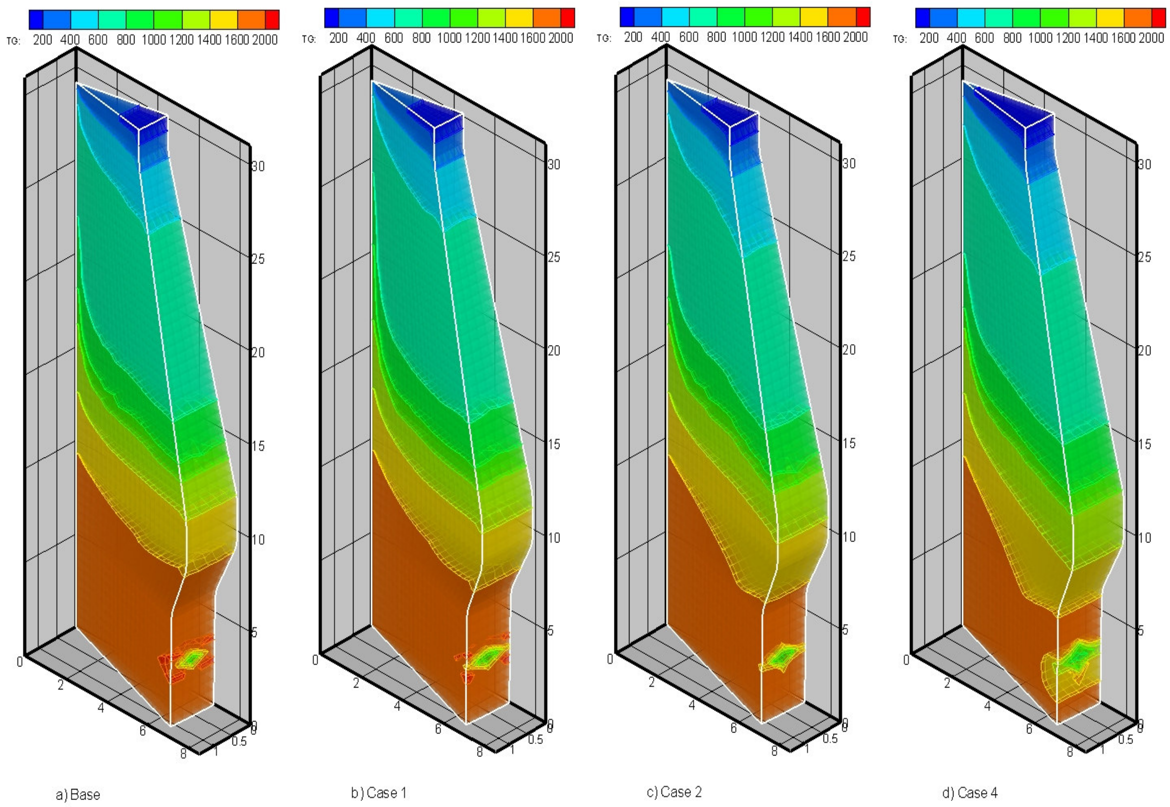


Figure 6 Inner temperature distributions for recycling CO2 operation

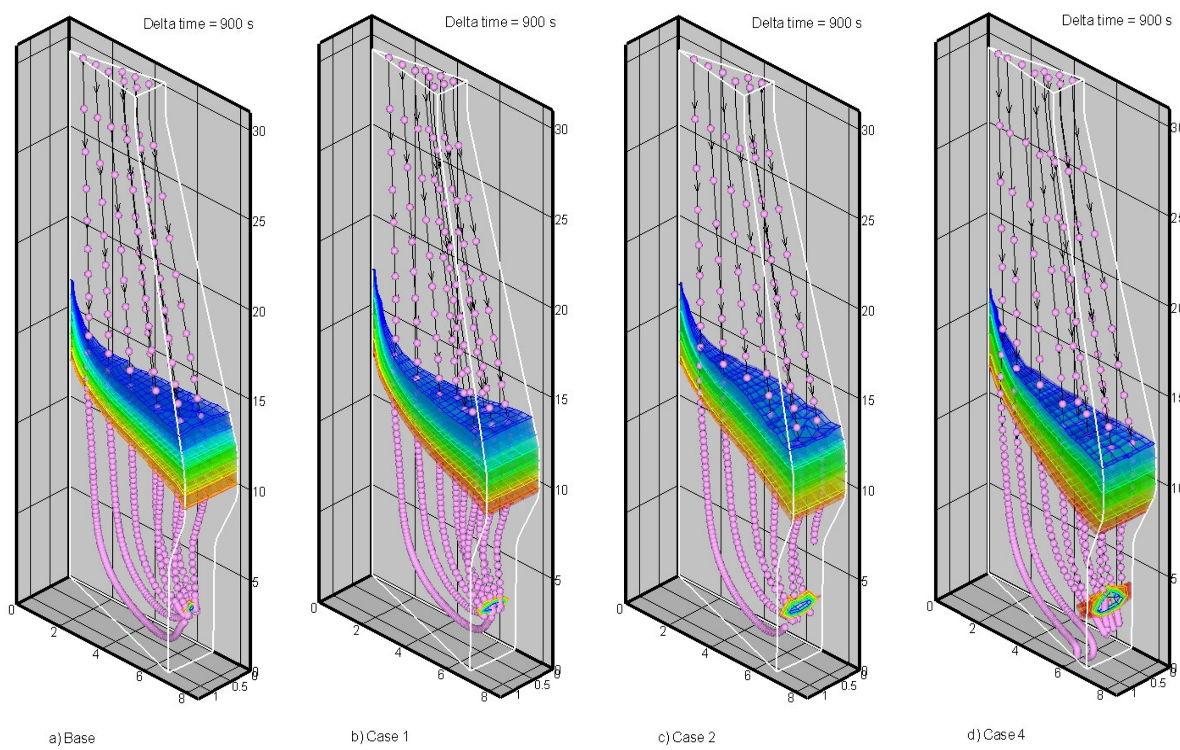


Figure 7 Model prediction of solid flow pattern and cohesive zone position

4- CONCLUSION

The model was able to analyze the performance of the blast furnace with high rates of gas injection. The model is based on transport equations of momentum, energy and chemical species of five phases coexisting simultaneously within the reactor. The recirculation of top gas with the enrichment of oxygen showed potential feasibility. Based on the simulation results the following conclusions is pointed out: 1) the productivity of the furnace could be increased up to 35% combining oxygen enrichment of 15% and CO_2 recycling of 100 Nm^3/t ; 2) Specific CO_2 emissions decreased about 18% ; 3) Fuel consumption slightly increased about 3kg/t and 4) Silicon content decreased to around 0.14%. Special concern is indicated by the model for high injection of CO2 due to formation of "bird nest" in the raceway region caused by endothermic reactions. The model indicated critical conditions for case 4 and lead to the conclusion of additional injection is not recommended for smooth operation.

5- LITERATURE

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