

Impact of operational parameters on fuel consumption of a blast furnace

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Abstract

Process analyses foster opportunities for identifying losses during the production process and consequently, provide courses of action to enhance the process with operational parameters that are compatible with the targeted results. In this study, a thermochemical model was developed in order to monitor the performance of coke-based blast furnaces, focusing on tools for calculating and graphically displaying parameters that facilitate interpretation of the internal phenomena. To apply the model, a database was prepared based on operational simulations of blast furnaces. The input parameters for the model consisted of the properties and consumption of raw materials and the mass and thermal balances of the process. The thermochemical model is based on the calculation of the degree of reduction of the metallic burden in the preparation zone, defined as the omega factor. It was found that the omega factor varies significantly with the CO/CO₂ ratio and %H₂ of the top gas. The results obtained by applying this model were coherent, thus validating it as a predictive tool for assessing the sensitivity of the omega factor, which has a major effect on carbon consumption.

Keywords: blast furnace; thermochemical model; specific carbon consumption; mathematical models; thermal control.

1. Introduction

1.1 Importance of controlling fuel consumption in blast furnaces

Because of current competitiveness in the steel industry, reducing costs with raw materials is essential. Because fuel consumption accounts

for approximately 40 to 60% of the cost of hot metal, developing systems that enhance its control is important for reducing costs, aside from also

contributing to thermal control and, consequently, to the operational stability of the blast furnace. (Ujisawa *et al.*, 2005).

1.2 Thermochemical models

Thermochemical models perform extensive calculations based on the mass and thermal balances of the process. This control allows corrections to be made to the process as soon as any deviation begins to occur, significantly reducing the risk of abrupt cooling, variations in the quality of the hot metal, and fuel consumption. (Vehec and Zhou, 2011).

In this regard, the system indicates the need to change the fuel rate (loaded

fuel) based on changes in the fuel consumption rate of the blast furnace. In other words, the thermochemical model calculates the amount of carbon consumed at a certain point in time, which may be different from the amount being loaded. To maintain the thermal level of the blast furnace at a constant, the two values should be equal (Jindal *et al.*, 2007).

In addition to the furnace's ther-

modynamics, these models divide the blast furnace into preparation zone and elaboration zone and consider that the gases enter the preparation zone in thermodynamic equilibrium with the iron and the wustite. The thermochemical model is based on the degree of reduction of the metallic burden in the preparation zone, making it possible to calculate the omega factor (Jindal *et al.*, 2007; Harvey and Gheribi, 2014).

Preparation zone

The temperatures of the preparation zone are below that at which the solution loss reaction occurs. Thus, if the carbon does not react in this region, it can be treated as a reactor in which the load is dried, pre-heated, and pre-reduced by the ascending gases. The reaction between

the C and CO₂ [$C_{(s)} + CO_{2(g)} \rightarrow 2CO_{(g)}$] is named solution loss. Its main characteristics are a high activation energy (temperature > 950°C) and the fact that it is endothermic (Zeng *et al.*, 2010).

The ideal operation of a blast furnace is when the following conditions are

present in the preparation zone:

- a) Perfect gas-solid thermal exchanges;
- b) All hematite (Fe₂O₃) is reduced to wustite (FeO_{1.05});
- c) The gases enter the preparation zone in thermodynamic equilibrium with the iron and wustite.

Elaboration zone

The main characteristic of the elaboration zone is that the carbon reacts. Therefore, all the thermal charge transferred to it is translated into an increase in specific carbon consumption (Zeng *et al.*, 2010).

In the elaboration zone, the gases enter the flame temperature through the combustion zone and exit at the temperature at which the solution loss reaction of the carbon ceases to occur (950°C for coke-based

blast furnaces).

The carbon in this zone reacts with the CO₂, becomes incorporated with the hot metal, and is burnt in the combustion zone, generating the reducing gases at high temperatures.

Omega factor

The omega factor (ω) index measures the performance of the mass transfer in the

blast furnace. This index strongly influences carbon consumption and indicates the con-

dition of reduction of the metallic burden in the preparation zone (Shen *et al.*, 2015).

$$\omega = \left(\frac{O}{Fe}\right)_{\text{goes on to the elaboration zone}} - 1.05 \quad (\text{Eq. 1})$$

where: ω = omega factor;

$\left(\frac{O}{Fe}\right)_{\text{goes on to the elaboration zone}}$ = ratio between oxygen atoms and iron atoms from the

metallic burden that goes on to the elaboration zone. If the metal load from the blast furnace consists only of Fe₂O₃ and this ox-

ide is entirely reduced to wustite (FeO_{1.05}) in the preparation zone, the omega factor will be equal to:

$$\omega = 1.05 - 1.05 = 0 \quad (\text{Eq. 2})$$

Similarly, if the Fe₂O₃ does not undergo any reduction in the preparation zone, the omega factor will be equal to:

$$\omega = \left(\frac{3}{2}\right) - 1.05 = 0.45 \quad (\text{Eq. 3})$$

Thus, the omega factor varies from 0 to 0.45, with 0 as the best condition and 0.45 the worst. The omega factor can be calculated through analysis of the

top gas from the blast furnace. Because the CO/CO₂ and H₂/H₂O ratios that enter the preparation zone are known, a comparison of these values with the ratios

of the top gases allows the extent of the oxide reduction to be evaluated, which thus allows the value of the omega factor to be calculated.

2. Materials and methods

Thermochemical model

The method used for analysis was based on the thermodynamic balances of different regions of the blast furnace.

The thermochemical control proposed in this study is based on six distinct types of information: data on the top gases, the load, the blast, the hot metal, the slag,

and the thermal losses. The information on the top gases is the most important (main sensor) in this type of control, because any change in blast furnace process is instantly reflected in changes to the temperature and composition of these gases (Torsell *et al.*, 1992).

The set of calculations described below constitutes the thermochemical model (Castro *et al.*, 2003):

- A mass balance in the elaboration zone allows an expression of the blasted air volume (V) to be calculated according to the degree of reduction of the metallic

burden originating from the preparation zone (omega factor - ω) and the carbon that is being consumed (C);

- A thermal balance in the elaboration zone allows the amount of heat consumed

(and therefore the carbon consumption), the specific air volume to be calculated;

- A mass balance in the preparation zone allows the volume and the composition of the top gases to be calculated;

- The calculated ratio CO/CO_2 of top gas is compared with the measured results to validate the omega factor.

The flowchart for these calculations is shown in Figure 1.

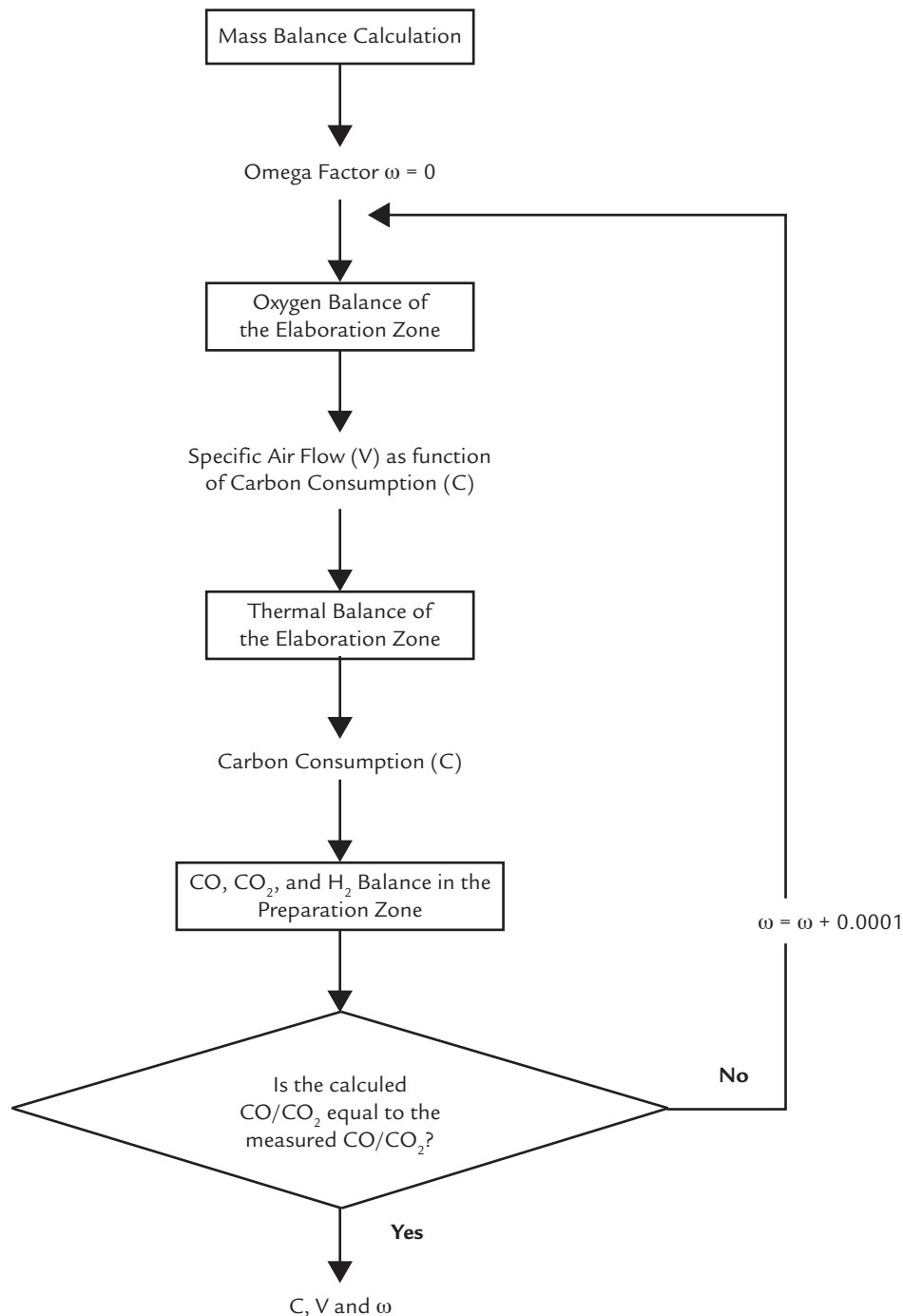


Figure 1
Calculation scheme
of the thermochemical model.

3. Results and discussion

3.1 Analysis of the variables

In order to better understand the impact and sensitivity of the process, raw material, hot metal, and slag parameters, an analysis was performed based on the calculations and results from the thermochemical model for an industrial blast furnace with an internal volume of 3050 m³. The results were analyzed using

the software program Minitab (statistical analysis software). The impact of some variables on carbon consumption is shown in Figure 2. As can be observed, the inclination of the line indicates whether the variable in question is directly or inversely proportional to the carbon consumption; the greater the inclination, the greater is

the impact. Thus, the variable with the highest impact is the %CO/%CO₂ ratio in the top gas, demonstrating the importance of reliable analysis of the gas. It is worth stressing that these results are only valid for the ranges of values of the variables used in the simulation of the thermochemical model.

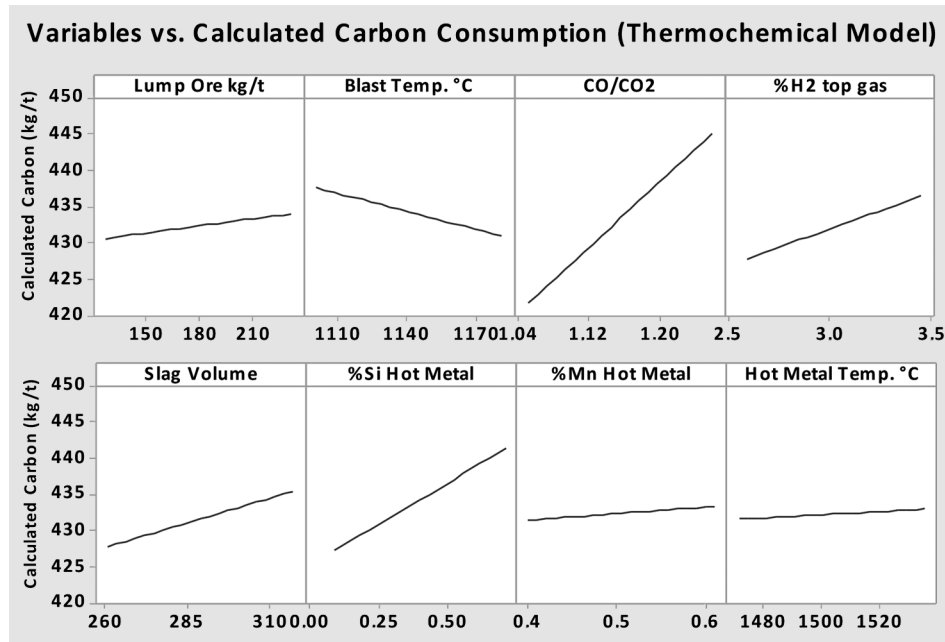


Figure 2
Impact of variables vs. carbon consumption.

- Lump ore: increased lump ore consumption results in increased carbon consumption owing to its low reducibility in comparison to sinter and pellet (hematite iron ore was used);
- Blast temperature: increased blast temperature results in reduced carbon consumption owing to the greater input of heat in the elaboration zone;
- %CO/%CO₂ top gas ratio: this is the variable with the highest inclination of the line, that is, with the greatest impact on carbon consumption. It is related to the use of CO gas in the preparation zone. The lower the %CO/%CO₂ ratio, the lower the carbon consumption;
- %H₂ top gas: indicates the use of H₂ in the preparation zone, but it should not be analyzed alone because of the impact of the coal injection rate on %H₂ at the top. In other words, an increase in %H₂ may be associated with

an increased injection rate and not with the use of H₂ in the elaboration zone. Thus, for a fixed injection rate, increasing %H₂ of top gas results in increased carbon consumption;

- Slag rate: increased slag rate results in increased carbon consumption owing to the need to warm and melt the slag;
- %Si hot metal: the greater the %silicon in the hot metal, the higher is the carbon consumption. The %Si is associated with the endothermic reaction of the incorporation of silicon into the hot metal;
- %Mn hot metal: same analysis as silicon; however, the reaction requires less heat and thus the inclination of the line is different;
- Hot metal temperature: the higher the working temperature of the hot metal, the greater is the carbon consumption required to raise the temperature of the metal load to the desired temperature.

The impact on fuel consumption of the parameters calculated through the thermochemical model such as slag rate, %lump ore in the burden, %Si of the hot metal, %Mn of the hot metal, blast temperature, and gaseous yield (Eq. 4) are given in Table 1. The table also presents the results reported by Castro (2002) and Spence *et al.* (1997) for comparison. The results obtained by Flint (Castro, 2002) originated from a statistical analysis of the results of several blast furnaces in the world, which considers the statistical impact of the variables on fuel consumption. The results presented by Spence were obtained in a specialized blast furnace control system based on mathematical models. An analysis of Table 1 shows that the results of the thermochemical model are consistent with those found in other studies in the literature.

$$\eta = \frac{\%CO_2}{\%CO + \%CO_2} \times 100 \quad (\text{Eq. 4})$$

Variable	Variation	Fuel Consumption Impact (kg/t)		
		Thermochemical Model	Flint (Castro, 2002)	Spence <i>et al.</i> , 1997
Slag rate	+10kg/t	1.49	1.50	2.50
%Lump ore	+1%	0.52	-	-
%Si hot metal	+1%	22	20	21
%Mn hot metal	+1%	5.10	10.00	-
Blast Temp.	+10°C	-0.99	-1.10	-0.86
Yield top gas	+1%	-5.71	-	-4.60

Table 1
Table of impacts obtained through the thermochemical model vs. studies from the literature (Castro, 2002; Spence *et al.*, 1997).

3.2 Relationship between the omega factor and fuel consumption

Another important result from the thermochemical model is the calculation of the omega factor (ω), which is directly related to carbon con-

sumption. The relationship between the omega factor and real carbon consumption is shown in Figure 3. Note that there is a strong correlation

between the variables ($R^2 = 79.3\%$), reinforcing the importance of knowing the omega factor.

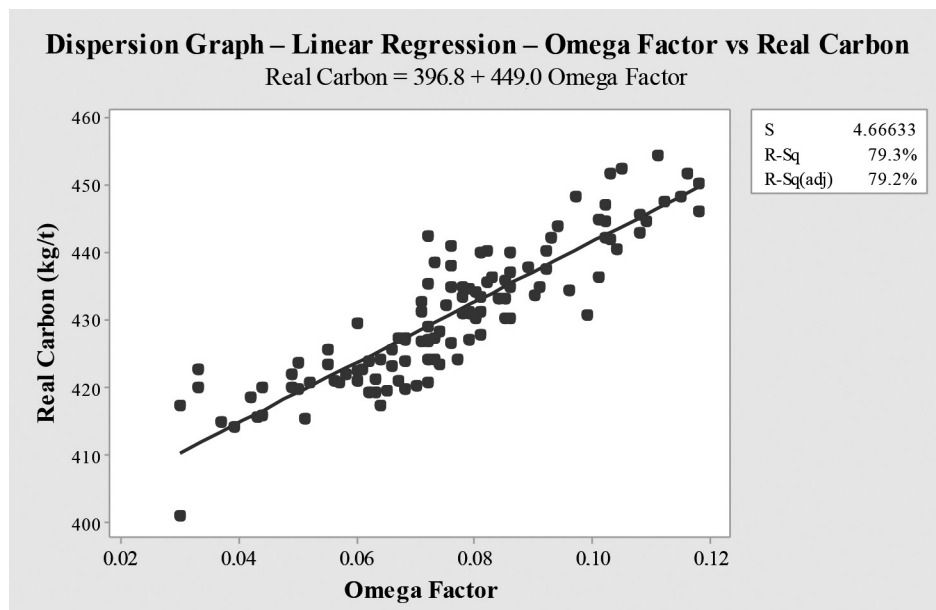


Figure 3
Correlation between omega factor and real carbon consumption.

Through an analysis using the results of the thermochemical model and the statistical software program Minitab, an equation to predict the omega factor can

be defined. The use of $\%H_2$ in the preparation zone is difficult to calculate because this region contains $H_2O_{(g)}$ originating from the evaporation of water from the

raw materials. Thus, an equation was formulated to correlate the $\%H_2$ at the top by using the coal injection rate and $\%H_2$ of the coal (Eq. 5).

$$\text{Ratio } \frac{H_2 \text{ coal}}{H_2 \text{ top}} = \frac{\%H_2 \text{ coal} \times \text{PCR}}{\%H_2 \text{ top}} \quad (\text{Eq. 5})$$

where: PCR = pulverized coal rate in kg/t

It is clear that any variation in the H_2 content from another source in the process will affect the calculation of the omega factor, such as variation in the injection humidity and the entry of water in regions of the blast furnace with sufficient temperature

to result in the dissociation of the water.

Regression analysis evaluates the relationship between independent variables (predictive variables) and a dependent variable (response), providing an equation that describes this relationship.

Table 2 shows the regression analy-

sis (obtained through statistical analysis performed by minitab software) with the predictive variables $\%CO/\%CO_2$ ratio and $\%H_2\text{coal}/\%H_2\text{top}$ ratio and the response variable omega factor. Evaluating the p value (probability of significance) for each predictive variable, significance

Regression Analysis: Fator Omega versus %CO/%CO2; %H2 coal / %H2 top gas						
Analysis of Variance						
Source	DF	Adj SS	Adj MS	F-Value	P-Value	
Regression	2	0.046051	0.023026	3296.71	0.000	
%CO/%CO2	1	0.040906	0.040906	5856.81	0.000	
%H2 coal / %H2 Top gas	1	0.003099	0.003099	443.72	0.000	
Error	111	0.000775	0.000007			
Total	113	0.046827				
Model Summary						
	S	R-sq	R-sq(adj)	R-sq(pred)		
	0,0026428	98.34%	98.31%	98.23%		
Coefficients						
Term	Coef	SE Coef	T-Value	P-Value	VIF	
Constant	-0.22071	0.00713	-30.98	0.000		
%CO/%CO2	0.33737	0.00441	76.53	0.000	1.01	
%H2 coal / %H2 Top gas	-0.05069	0.00241	-21.06	0.000	1.01	
Regression Equation						
Fator Omega = -0.22071 + 0.33737 %CO/%CO2 - 0.05069 %H2 coal / %H2 Top gas						

Table 2
Regression analysis for the omega factor.

can be concluded owing to the p value < 0.05 (95% confidence), as highlighted in Table 2. In relation to the correlation coefficient between the omega factor calculated by the regression and the omega

4. Conclusions

- Based on the simulations of the thermochemical model, the omega factor was calculated, and it was found that it varies significantly with the CO/CO₂ ratio

- The thermochemical model developed for the control of a coke-based blast furnace can be perfectly applied as long as the required information

factor from the thermochemical model, an excellent result was obtained, with $R^2 = 98.31\%$. The regression equation to predict the omega factor is highlighted in Table 2. Based on the obtained equation, it

and the %H₂ of the top gas. A positive correlation was found between the CO/CO₂ ratio and the omega factor, whereas a negative correlation was found between the

is reliable, and thus high precision in the top gas analysis (CO, CO₂, and H₂) is required.

- The omega factor can be cal-

is possible to calculate the omega factor and consequently anticipate actions in thermal control of the blast furnace using the equation with factor omega \times consumption of carbon (shown in Figure 3).

H₂ coal/H₂ top ratio and the omega factor.

- The omega factor has a major effect on carbon consumption. The relationship found was:

$$\text{Real Carbon Consumption} = 396.8 + 449.0 \times \text{Omega Factor} \quad (R^2 = 79.3\%)$$

culated based on the %CO/%CO₂ data from the top gas and the %H₂ coal/%H₂ top ratio, according to the following equation:

$$\text{Omega Factor} = -0.22071 + 0.33737x \frac{\%CO}{\%CO_2} - 0.05069x \frac{\%H_2 \text{ coal}}{\%H_2 \text{ top}} \quad (R^2 = 98.31\%)$$

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