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Original Article

# Thermo-chemical model for blast furnace process control with the prediction of carbon consumption

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ABSTRACT

The operational stability of a complex process such as the blast furnace is under constant threat owing to variation in the quality of raw materials as well as other operating conditions. Significant cost reductions can be achieved with adequate control of this process. Hence, mathematical models have proven to be useful in the thermal control of blast furnaces with regards to the fuel consumption and operational stability of these reactors. The thermo-chemical model calculates the hourly carbon consumption, which allows the operator to adjust for the aiming quantity of carbon. A strong correlation is observed between the results of the model and the actual results from the process. Thus, the model provides conditions for the operator to anticipate carbon behavior, and thus prevent large variation in the thermal properties of the blast furnace and provide high levels of operational safety.



## 1. Introduction

The aim of the ironmaking area in the steel industry is to safely produce hot metal at the lowest cost and within the specifications of the steel mill. To achieve this objective, many efforts have been made in the past few years such as improving the quality of the raw materials, equipment, facilities, and theoretically investigating the process phenomena.

Various phenomena that take place inside a blast furnace are still not clearly explained. Therefore, blast furnace operation models have been developed with the aim of predicting operational deviations and perfecting the process to guarantee the stability of the blast furnace and to reduce fuel consumption [1–3].

The blast furnace operation is usually investigated with two objectives: predicting the process indicators and understanding the internal blast furnace phenomena. These two

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objectives can be studied by different methods, including industrial-scale investigations, pilot experiments (in laboratory), and mathematical models. Industrial-scale investigations contributed to the understanding of the internal aspects of the blast furnace by dissecting it. These investigations could also be conducted by sampling the material of the tuyeres; however, such techniques are difficult to use since they require stopping the blast furnace and are costly. Pilot experiments are also conducted to understand the internal phenomena of blast furnaces, but they are not able to completely represent the phenomena of a real blast furnace and are also associated with high costs. Hence, mathematical models have played an important role in predicting process indicators and investigating the internal phenomena of blast furnaces [4].

The thermal control for most blast furnaces is still corrective; a measure is only taken after the observation of a deviation in the range of composition or temperature of the hot metal. Therefore, the thermal control often depends on the operator's experience and the response to the problem could be slow, i.e., a large variation is introduced in the quality and temperature of the hot metal and in the fuel consumption.

To improve the stability of the blast furnace, a thermo-chemical model was developed for process control. The purpose of the thermo-chemical model is to assist in operator decision-making regarding fuel consumption in blast furnaces. This model calculates the amount of carbon consumed at a given moment and establishes that the loaded quantity should equate to the consumption value in order to maintain a constant thermal level in the blast furnace.

Thermal control of the process is critical for the hot metal production in blast furnaces, since greater thermal control improves product (hot metal) quality and increases process efficiency, such as the reduction of the total energy (fuel) consumption [5–7].

In addition to thermodynamics, the thermo-chemical model applies the concept of dividing the blast furnace into the preparation and elaboration zones, and considers the incoming gases in the preparation zone to be at thermodynamic equilibrium with iron and wüstite. The thermo-chemical model is based on the degree of reduction in metallic burden within the preparation zone [8].

The gas yield (usage of CO gas) or $CO/CO_2$ ratio, cited by Spence and Pritchard [9] and also discussed by Harvey and Gheribi [10], has a large influence on the fuel consumption. It can be observed that smaller $CO/CO_2$ ratios or better use of carbon monoxide results in the lower consumption of coke. Top gas analysis is the main sensor of the thermo-chemical model.

Hence, the control provided by the thermo-chemical model allows for corrections in the process as soon as the deviation occurs, decreasing the risk of abrupt cooling, improving the quality of hot metal and reducing fuel consumption [11].

The following are some of the advantages of applying an operational (thermo-chemical) model:

- Higher operational safety;
- Higher operational stability with lower production costs;
- Preventive detection of process phenomena.

## 2. Methodology

The thermo-chemical control proposed in the present study will be based on five different types of information: data from the top gases, burden, blow, hot metal, slag and heat loss. The information from the top gases is the most important (main sensor) in this type of control, because any alteration in the process causes instantaneous changes in the temperature and composition of these gases.

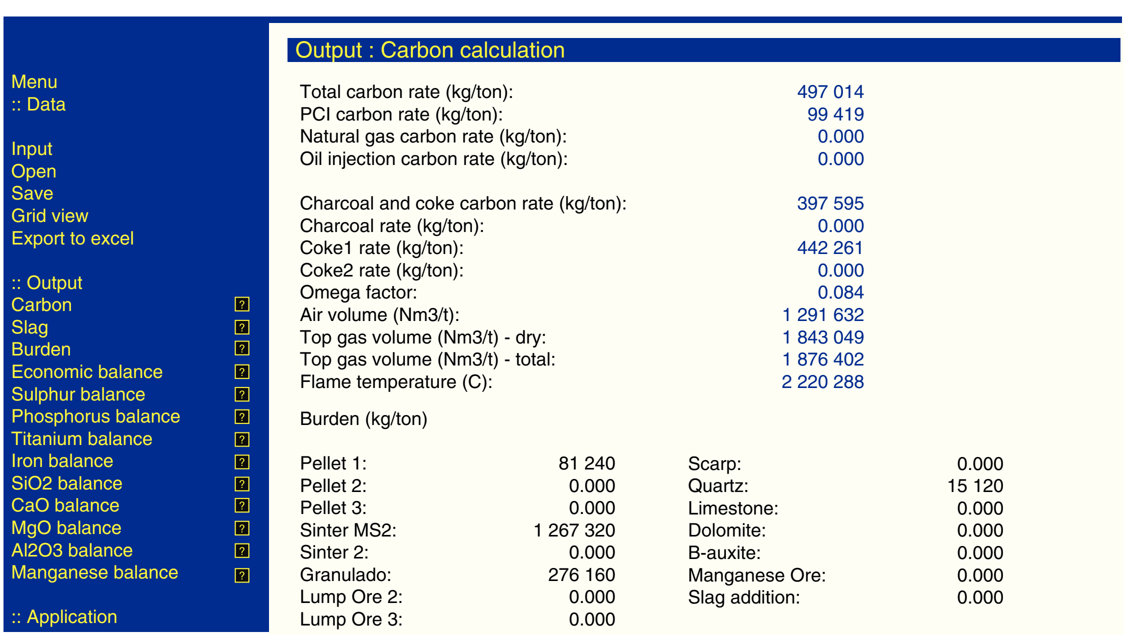


**Fig. 1 – Screen with the results of the thermo-chemical model.**

The control model was divided into five parts:

- Blast furnace definition
- Data organization and input
- Model calculations
- Data output
- Action by the operator

### 2.1. *Blast furnace definition*

The blast furnace employed for the validation and application of the model will be named Blast Furnace A in the present study, with an internal volume of 3050 $m^3$.

### 2.2. *Data organization and input*

To simulate real results and validate the thermo-chemical model, the reference period from January to June of 2016 (6 months) was defined. For this period, a daily database was created with all of the information required by the model.

### 2.3. *Model calculations*

The main objective of the control model is to calculate the carbon consumption at a specific moment so the operator can aim the quantity that is effectively consumed, thus maintaining a stable thermal level. The best model for this purpose is the thermo-chemical model.

The calculations consist of the following:

(1) mass balance for the elaboration zone, which allows the calculation of an expression with the volume of blown air in function of the degree of reduction of iron oxide from the preparation zone (Omega Factor – ω) and the carbon consumed;
(2) thermal balance of the elaboration zone, which allows the calculation of the amount of heat consumed and therefore the consumed carbon and the specific air volume;

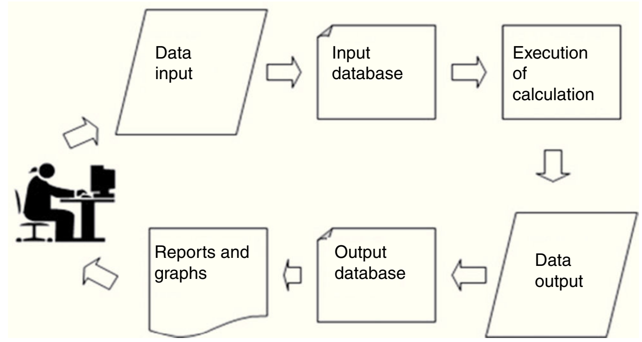


**Fig. 2 – Scheme of the proposed control model.**

(3) mass balance at the preparation zone, which allows the calculation of the volume and composition of the top gases and the degree of reduction of iron oxide sent to the elaboration zone (ω factor).

### 2.4. *Data output*

For each set of input data, the program calculates a corresponding set of variables, named output data. If the model operates online, the input and output data will occur instantaneously with the process variations.

The screen of the thermo-chemical model is illustrated in Fig. 1. The main result of the model is the expected carbon consumption.

### 2.5. *Actions by the operator*

After completing the simulation with real data and determining the calculated carbon consumption, the real and calculated carbon data were compared. In this step, the sensitivity of the model was verified in relation to the main operational parameters.

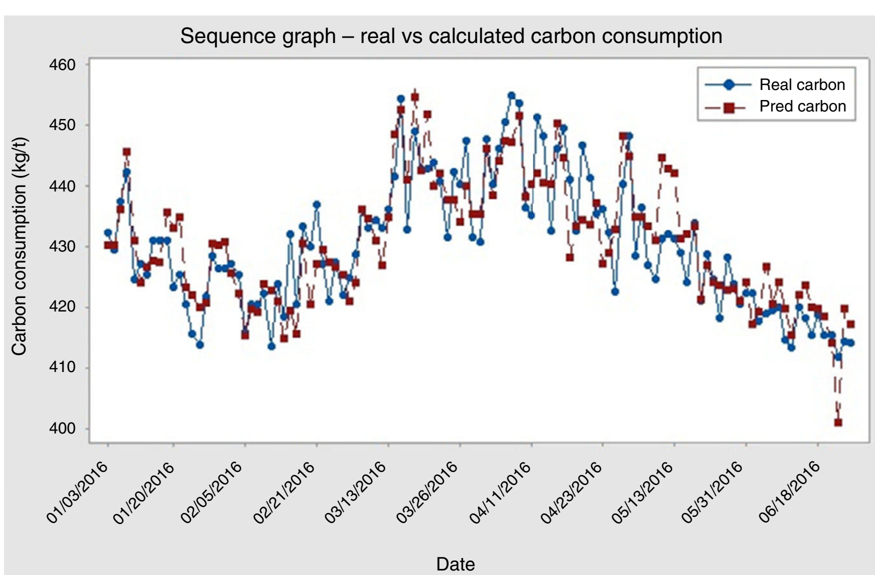


**Fig. 3 – Sequence graph for the calculated vs. actual carbon consumption.**

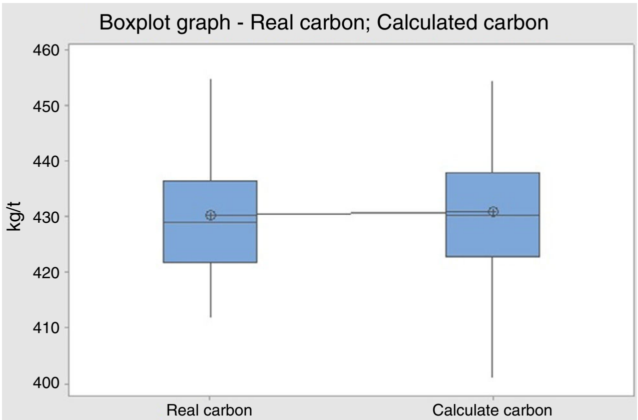


**Fig. 4 – Boxplot graph for the calculated vs. actual carbon consumption.**

With the validation from the analyses performed, the model was used by the operator for the process control with the objective of achieving greater assertiveness in the definition of the loaded carbon in relation to the consumed carbon (calculated by the thermo-chemical model).

Fig. 2 presents the scheme of the control model.

## 3. Results and discussion

For result evaluation, the Minitab software was used to mathematically verify the analyses performed. The studies by Campos [12] were used as reference for the analyses on Minitab.

During the validation of the thermo-chemical model, the calculated carbon consumption was analyzed. Figs. 3 and 4 show the sequence and boxplot graphs, respectively, comparing the results of the calculated and real carbon consumption by Blast Furnace A for each selected time period. The sequence graph indicates that the data sets follow the same trend and the boxplot graph shows that the means and dispersion of results are quite similar.

To verify the correlation of results, linear regression analyses were performed, as illustrated in the dispersion graph of Fig. 5. The correlation coefficient between the calculated and real carbon consumption ($R^2$) for Blast Furnace A is evidenced in Fig. 5. The analysis of the correlation coefficient ($R^2 = 71.5\%$) leads to the conclusion that there is a strong correlation between the variables, which can be proven statistically by analyzing the $P$-value of 0.000 (according to Table 1) [12]. $P$-values less than 0.05 lead to the conclusion that there is a significant correlation between the variables.

Hence, it can be said that the thermo-chemical model is sufficient for calculation of the carbon consumption by Blast Furnace A, and can be used for process adjustment with the objective of guiding operator action toward judicious decision-making regarding fuel consumption.

The specific carbon consumption (kg/t hot metal) is very much affected by the value of the omega factor. For an operation with low specific carbon consumption, the omega factor should be smaller, i.e., the process should develop a good efficiency of iron oxide reduction in the preparation zone [6,7].

The relationship between the omega factor and the actual carbon consumption is observed in Fig. 6. The strong correlation between the variables can be observed, which is consistent with the proposal of the thermo-chemical model and similar to the results cited by Castro and Tavares [13].

After validating the results from the thermo-chemical model with the operational data of Blast Furnace A, the online model was analyzed in the process. The online analysis of the thermo-chemical model is the last step for optimizing application of the model to assist the operator. The online evaluation was performed using the means of parameters every 2 h. Hence, every 2 h the operator will have a new result regarding fuel consumption to assist in the decision-making constituting blast furnace thermal control. Fig. 7 shows the set carbon consumption desired by the operator and the fuel consumption calculated by the thermo-chemical model.

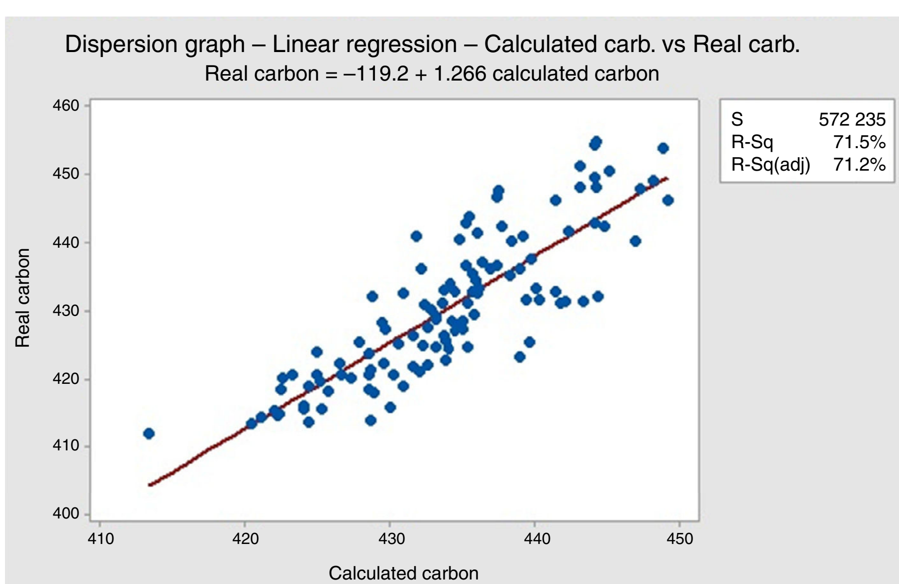


**Fig. 5 – Correlation graph for the calculated vs. real carbon consumption.**

**Table 1 – Regression analysis for the calculated vs. actual carbon consumption.**

The regression equation is
Real Carbon = −119,2 + 1,266 Calculated Carbon
S = 5,72235 R-Sq = 71.5% R-Sq(adj) = 71.2%

Analysis of variance

| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Regression | 1 | 9272.5 | 9272.51 | 283.17 | 0.000 |
| Error | 113 | 3700.2 | 32.75 | | |
| Total | 114 | 12972.7 | | | |

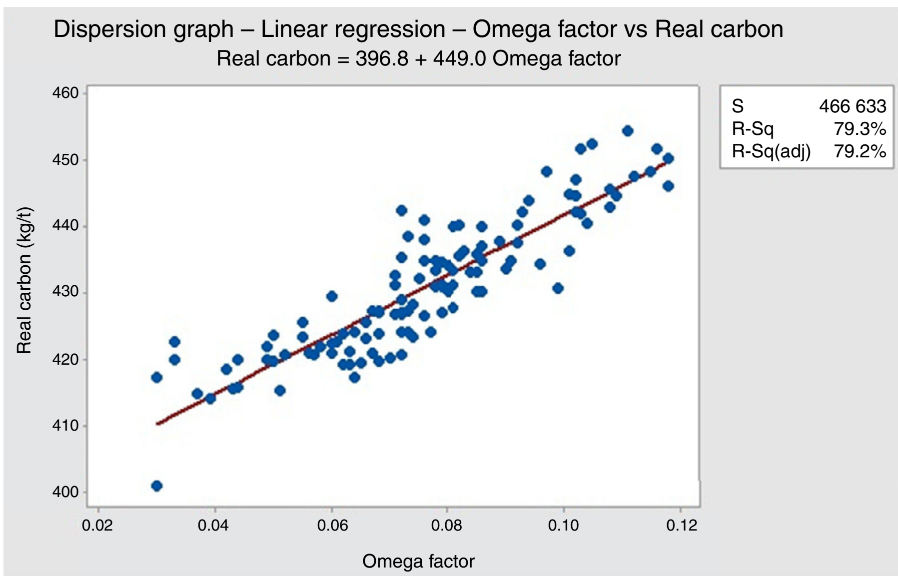


**Fig. 6 – Correlation graph for actual carbon consumption vs. omega factor.**

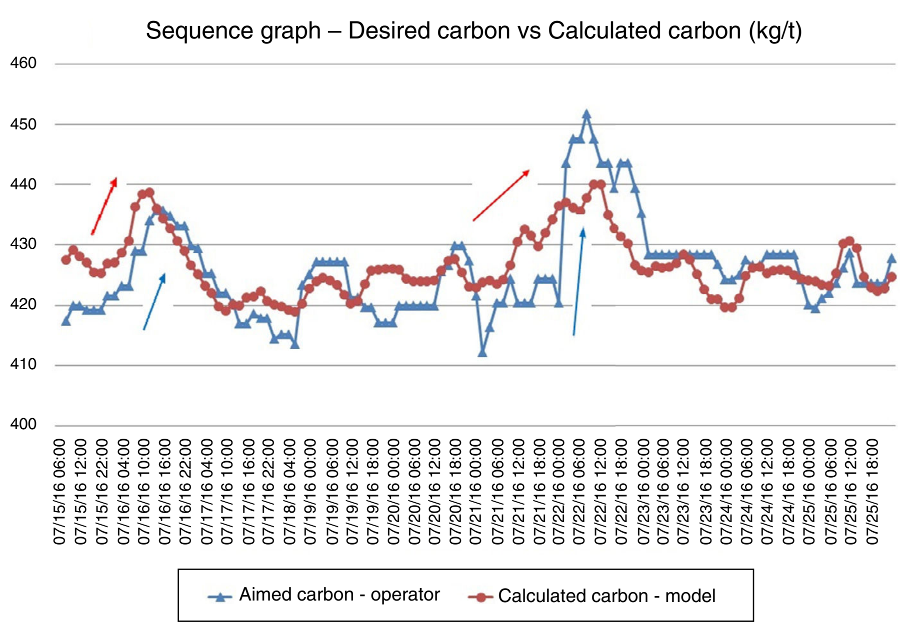


**Fig. 7 – Sequence graph for desired carbon vs. calculated carbon.**

The arrows in the figure indicate that the carbon calculated by the thermo-chemical model anticipates the operator's action. This is because the thermo-chemical model calculates the carbon consumption based on internal parameters of the blast furnace, such as the top gas result, and the operator acts on the carbon consumption with the analysis of the hot metal temperature, i.e., correctively.

The model trends allow the operator to anticipate the actions and reduce variation in the thermal level of the blast furnace. Despite the preventive evaluation of the process by the thermo-chemical model, the corrective action should continue because the model does not evaluate all parameters that affect the thermal level of the blast furnace. Some examples of situations in which the use of the model is not recommended are the entrance of water in the blast furnace (leaks in the staves or tuyeres) and conditions with high process instability.

## 4. Conclusions

- The control model developed for the control of a coke blast furnace is perfect employed. The calculated and actual results of Blast Furnace A show a strong correlation, thus validating the calculations of the model;
- The application of the model demonstrated that the operator is able to anticipate the carbon consumption control and avoid large variation in the thermal level of the blast furnace, thus providing higher operational safety (lower risk of cooling); i.e., the thermal control was no longer corrective and was instead preventive.
- The model is a powerful tool with great application in the blast furnace process, assisting the operators in their decision-making and preventing problems that can be avoided with analyses conducted for situations closer to the actual situation of the blast furnace, in a fast and simple manner.

## Conflicts of interest

The authors declare no conflicts of interest.

## Acknowledgements

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