EFFECT OF THE TYPE OF COAL INJECTED IN THE BLAST FURNACE TUYERES ON THE FUEL-RATE[1]

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Abstract

The injection of coal fines in the blast furnace tuyeres is one of the major means to reduce the pig iron production costs and the coke dependency of the process. When a change of the coal mixture injected is needed it is important to know the characteristics of the new mixture in order to achieve the process stability, to keep the productivity and reduce the pig iron production costs. The objective of this study was to analyze and develop a method for the calculation of the coke/coal substitution rate applied at the Usiminas blast furnaces, relating these results to the calorific value (and/or other variables) of the different coals injected. Besides, a model was developed for estimating the fuel-rate change as a function of the coal fines injection rate and the calorific value of the coals (or mixture) when the type of coal injected is changed. The heat input equivalence for each kg of fuel-rate determined was 5000 kcal. Considering an injection rate of 100 kg/t of pig iron, when a coal with a calorific value of 7500 kcal/kg is replaced by another one with 7700 kcal/kg, the fuel rate change is – 4 kg/t of pig iron, which means that for the same charge the injection rate can be reduced by 4 kg/t of pig iron. This correction of the fuel-rate (coke rate) change is a great help to the process stability, since the change of the coals (or coal mixture) injected results in larger or smaller variations of the blast furnace operation.

Key words: Blast furnace; Coal fines injection; Coke rate.

EFEITO DO TIPO DE CARVÃO INJETADO NAS VENTANEIRAS DO ALTO-FORNO NO CONSUMO DE COMBUSTÍVEIS (*FUEL-RATE*)

Resumo

A injeção de finos de carvão pelas ventaneiras dos altos-fornos é um dos principais meios de redução do custo de produção do gusa e da diminuição da dependência de coque no processo. Quando é necessário alterar a mistura de carvão injetada, um ponto importante é conhecer as características da nova mistura para obter a estabilidade do processo, a manutenção da produtividade e a redução nos custos de produção do gusa. O objetivo deste estudo foi avaliar/desenvolver uma metodologia de cálculo da taxa de substituição coque/carvão aplicada nos altos-fornos da Usiminas, correlacionando esses resultados com o poder calorífico (e/ou outras variáveis) dos diversos carvões injetados. Além disso, foi desenvolvido um modelo para estimar a variação no *fuel-rate* em função da taxa de injeção de finos praticada e do poder calorífico dos carvões (ou mistura), quando ocorre alteração do tipo de carvão injetado. O valor encontrado para a equivalência do aporte térmico para cada kg de *fuel-rate* foi de 5000 kcal. Considerando uma taxa de injeção de 100 kg/t de gusa, quando da troca de um carvão com poder calorífico de 7500 kcal/kg para outro, de 7700 kcal/kg, a variação no *fuel-rate* é de – 4 kg/t gusa, ou seja, para uma mesma carga, a taxa de injeção pode ser reduzida em 4 kg/t gusa. Essa correção da variação do *fuel-rate* (*coke-rate*) muito contribui na estabilidade do processo, já que as trocas dos carvões (ou misturas de carvões) injetados, em maior ou menor escala, sempre ocasionam variações na operação (marcha) do alto-forno.

Palavras-chave: Alto-forno; Injeção de finos de carvão; Coque-rate.

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1 INTRODUCTION

At Usiminas, the pig iron production increase at the blast furnaces associated with the interruption of oil injection in the tuyeres (1981) resulted in a high deficit of coke, allowing the implementation of the coal fines injection systems in the blast furnaces (1993). The injection of high pulverized coal rates aim a better adequacy to the coke balance and, at the same time, a reduction in the pig iron cost and an increase of the life of the horizontal furnaces batteries. Keeping high coal fines injection rates and high productivity in the blast furnace is a great technological challenge.

Nowadays many furnaces are operated with remarkable results of coal injection in a wide range of conditions. However, many questions related to the type of coal, particle size, maximum injection rate, temperature of the blown air, oxygen enrichment rate etc., remain without an answer. These questions are opportunities for research efforts in order to widen the knowledge on the fundamentals and operational practices of the coal injection.

In general, the studies on coal injection can be realized through experimental installations or through *in loco* measurements at the blast furnace *raceway*. The installations, in laboratory and/or pilot scale, try to consider the real characteristics of the combustion in the tuyeres, or more specifically in the *raceway* area, allowing a qualitative knowledge of the coal particle gasification/combustion under conditions pertaining the blast furnace operation. These installations are complemented by analysis and tests for the physical, chemical and structural characterization of the coal, besides the characterization of combustion gas products and the non burned carbon.

An estimate of a variation of the fuel-rate associated with a change of the coal type (or of the coal mixture) injected in the tuyeres contributes for the process stability, for keeping the productivity and for reducing the pig iron production costs.

In this context, the objective of this study was to analyze and develop a method for the calculation of the coke/coal substitution rate applied at the Usiminas blast furnaces, relating these results to the calorific value (and/or other variables) of the different coals injected. Besides, a model was developed for estimating the fuel-rate change as a function of the coal fines injection rate and the calorific value of the coals (or mixture) when the type of coal injected is changed.

2 METODOLOGY

The coal injection at Usiminas started in 1993. From there on, dozens of coals were used besides binary mixtures of coals. The complete data bank of the characteristics of the coals used and the results at the blast furnace is available. Every coal acquired for injection at the blast furnaces is characterized at the arrival and combustion simulations were performed. The combustion experiments were realized on the pulverized coal combustibility simulator at the Usiminas Research Center.

The development of this work using statistical methodology was based on the industrial results obtained at the Usiminas blast furnaces.

Considering the extension of the data bank (started in1993), a selection of the time period to be used in the development of the work was necessary. The option of adopting the results from all three blast furnaces or only one specific furnace was also evaluated.

The variables which have the biggest influence on the substitution rate at the Usiminas blast furnaces were determined and subsequent statistical analysis of the selected data was conducted.

From the statistical methodology adopted and the evaluations realized a new model (equation) was defined for the calculation of the substitution rate.

In a second step an estimate of the fuel-rate variation resulting from the change of the coal or mixture injected was searched. For this purpose, the substitution rate values obtained by the developed model were correlated to the calorific values of the various coal mixtures used in the process.(1)

2.1 Selection of the Industrial Data

The great volume of available data for the coal fines injection at the Usiminas blast furnaces include not only a large time interval but also three blast furnaces with particular operational characteristics. Therefore the evaluations were concentrated in a restricted period of time. At first the data concerning the blast furnaces No. 1 and 2 were not considered, since these furnaces do not have adequate distribution systems and show larger variations in the operational results. The periods of reforms and great interventions on the equipment were also discarded. As a result, only the data relative to the blast furnace 3 (BF 3) from September 2002 till December 2006 were adopted.

3 RESULTS AND DISCUSSION

3.1 Operational Data of Blast Furnace 3

The construction of the data bank including the period from September 2002 till December 2006, with a total of 70 data sets, was based on the physical and chemical properties of the coals, as well as the operational parameter of BF3.

Table 1 shows the minimum, maximum and average values of the main variables analyzed.

Table 1– Main data used.

Characteristics of process and chemical and physical analysis data				
Variable	**Unit**	**Minimum value**	**Maximum value**	**Average value**
Injection Rate	(kg/t)	126.50	155.50	141.95
Calorific Value	(kcal/kg)	6999	7612	7275
HGI	(%)	58	93	75
Moisture	(%)	0.58	1.16	0.80
< 200mesh	(%)	76.90	85.63	81.28
Substitution Rate	(-)	0.817	1.079	0.965
Volatile Mater	(%)	18.57	33.42	24.22
Fixed Carbon	(%)	58.39	78.28	66.48
Carbon	(%)	74.81	81.3	77.59
Hydrogen	(%)	3.52	4,88	4.27
Oxygen	(%)	1.81	8.79	6.06
Ash	(%)	7.11	10.69	9.42

3.2 Data Analysis and Model Generation

The main variables which in principle should have a relation with the coal substitution rate of BF3 were analyzed with the aid of the software *Statgraphics Plus®*.

Firstly the data distribution was realized for a judicious analysis of all collected variable, checking the minimum, maximum and average of each set. The values considered as outliers were eliminated from the data bank.

After this effective data selection, several statistical analyses were realized using *Statgraphics Plus®* in order to determine which variables were actually relevant to describe the coal substitution rate model. The first analysis is shown in Figure 1. This is a multi-variable analysis which shows if there exists a dependency of the coal substitution rate on each one of the variables considered, the respective correlation coefficients being shown in Table 2.

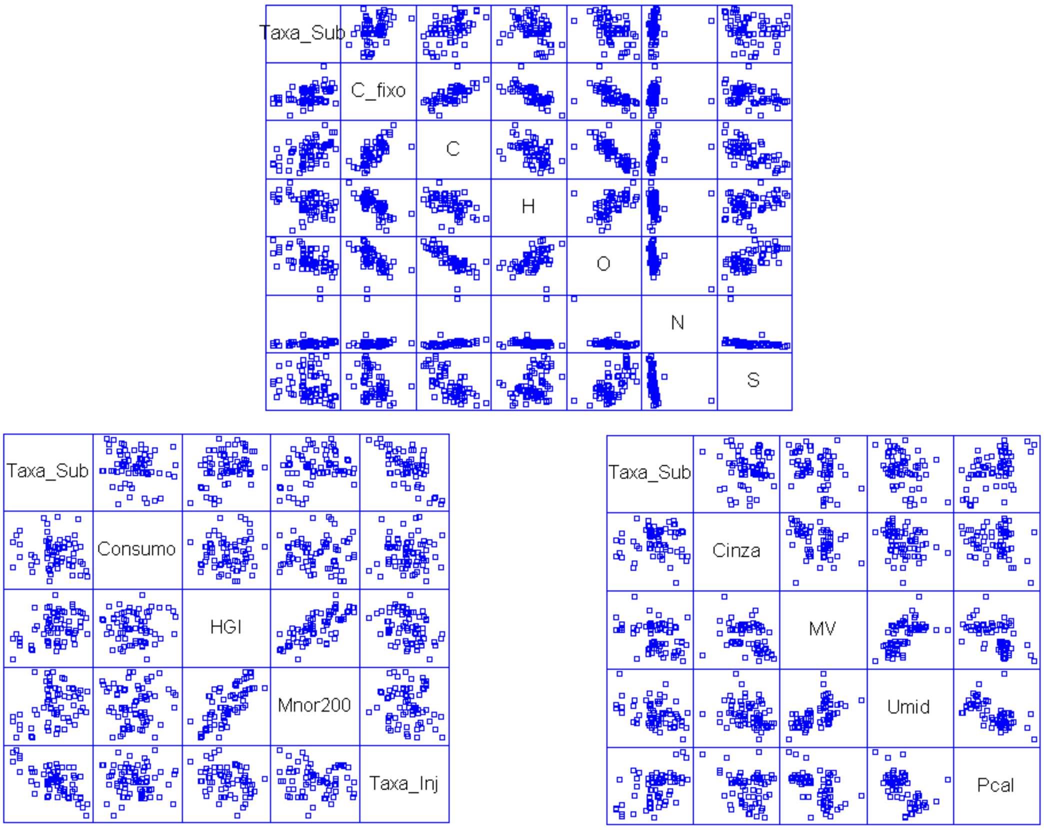

Figure 1 – Mosaic of dispersion diagrams between the substitution rate and the other variables.

Table 2 – Correlation coefficients for the mosaic of dispersion diagrams.

Correlation coefficients between the substitution rate and the other variables					
Variable	**Value**	**Variable**	**Value**	**Variable**	**Value**
Injection rate	-0.6467	Fixed carbon	0.3643	Sulfur	-0.1690
Calorific value	0.4989	HGI	0.3639	Nitrogen	0.1602
Carbon	0.4978	MV	-0.3437	Consumption	-0.1307
Oxygen	-0.4719	Hydrogen	-0.3109	Ash	0.0319
Moisture	-0.3824	< 200mesh	0.2962		

The observation of the mosaic and the correlation coefficient values generated by this analysis indicate that only the variables carbon and oxygen contents, coal calorific value and injection rate in the blast furnace show a good relation with the substitution rate, each variable having a correlation coefficient higher than 0.45, in modulus. The other variable are very disperse and/or have no relation. However, as observed in the preliminary statistical analysis, the variables carbon and oxygen contents and the calorific value are correlated with each other, affecting the dependent variable in an equivalent way, which leads to the conclusion that one of them is sufficient, beyond the injection rate, to describe the final model for the substitution rate. Therefore, for the simplification of the model without any quality loss, anyone of these three variables can be chosen. In this work, the carbon content was chosen, and the final model was written as a function of the variables injection rate in the blast furnace and carbon content.

In the sequence, the evolution of the four variables considered as most relevant as a function of the substitution rate was analyzed, as shown in Figure 2.

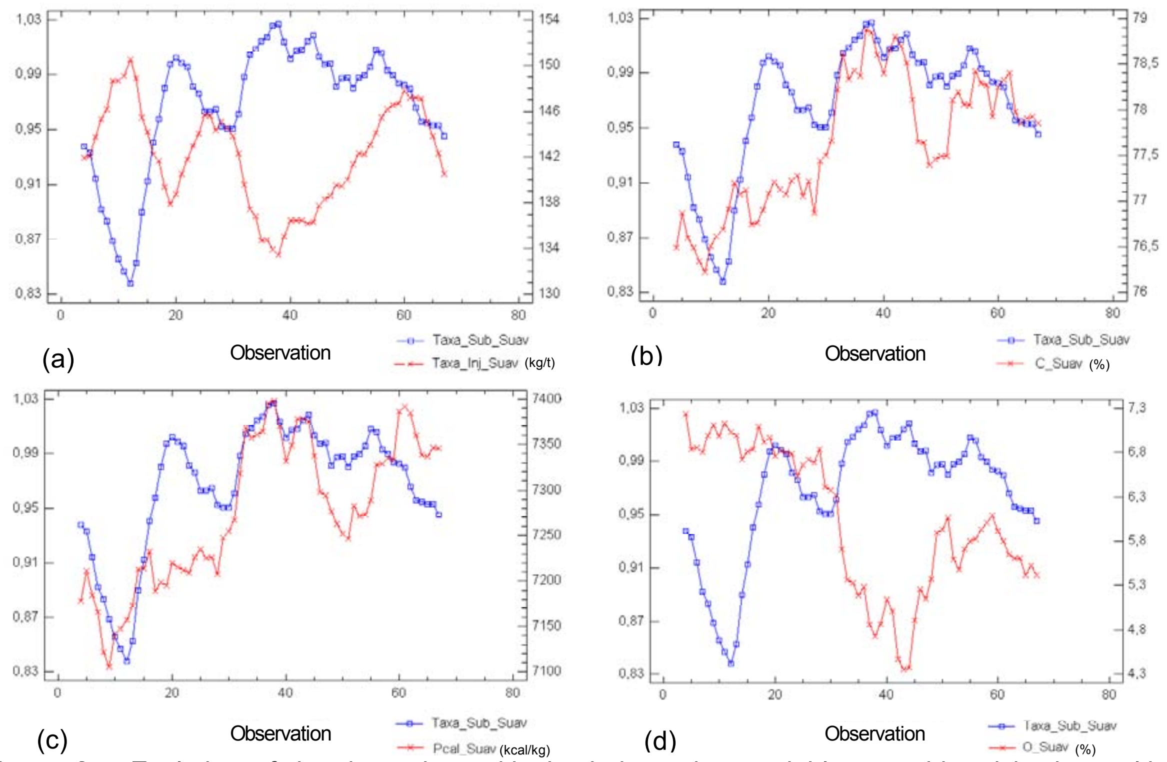

Figure 2 – Evolution of the dependent with the independent variables considered in the multiple analyses. (a) Substitution rate x injection rate; (b) substitution rate x carbon; (c) substitution rate x calorific value; (d) substitution rate x Oxygen.

The same tendencies related earlier can be seen in Figure 2, that is, the substitution rate has an indirect relation with the oxygen content and with the injection rate, increasing when these variables decrease, and a direct relation with the carbon content and the calorific value, increasing when these variables increase.

Finally, recognizing that these four variables are statistically relevant for the creation of the required model, a linear multiple regression was attempted, also using *Statgraphics Plus®*. With the aim of optimizing and simplifying the model without any loss in the final quality, an option (*Forward Selection*) was selected in the processing of the multiple regression, which verifies if there are sets of variables with similar effects in the dependent variable. As seen in the preliminary analyses, this behavior is observed in three relevant variables. Therefore, only one variable was chosen for the final model equation (equation 1), leaving the substitution rate (*Taxa_Sub*) as a function of the carbon content (*C*) and the injection rate (*Taxa_Inj*). It should be emphasized that the same procedure can be used if all the variables studied are selected, resulting in the same final model:

$$Taxa\_Sub = 100 \cdot (61.675 + 1.462 \cdot C - 0.554 \cdot Taxa\_Inj) \quad (1)$$

with a r^2 of 51.50% and correlation coefficient of 0.7176.

Besides the relation given by equation 1, two additional equations were suggested, considering the ratio carbon/injection rate (C/Taxa_Inj), since the carbon content is directly proportional to the substitution rate, while the injection rate is inversely proportional. Equations 2 and 3 show these relations:

- linear → $Taxa\_Sub = a \cdot \left(\frac{C}{Taxa\_Inj} \right) + b$; (2)

- logarithmic → $Taxa\_Sub = a \cdot \ln\left(\frac{C}{Taxa\_Inj} \right) + b$. (3)

It is important to emphasize that the ratio C/Taxa_Inj is, in itself, a non linear term.

After the single regression using equations 2 and 3, the results shown in the equations 4 and 5 are obtained:

- linear → $Taxa\_Sub = 1.5386 \cdot \left(\frac{C}{Taxa\_Inj} \right) + 0.1218$ (4)

with r^2 of 49.91% and correlation coefficient of 0.7065;

- logarithmic → $Taxa\_Sub = 0.8542 \cdot \ln\left(\frac{C}{Taxa\_Inj} \right) + 1.48$ (5)

with r^2 de 50.54% and correlation coefficient of 0.7109.

The plots of the regression in equations 4 and 5 are presented in Figure 3.

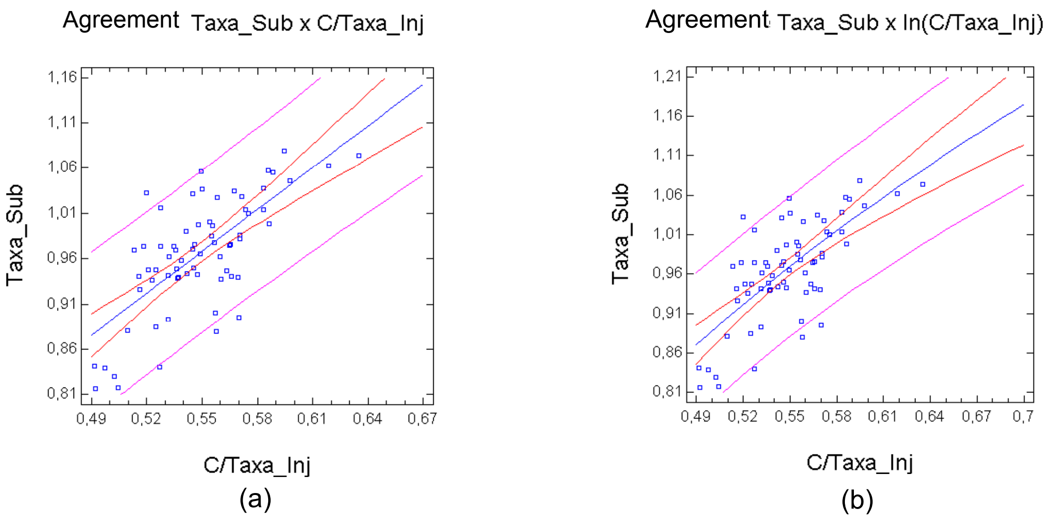

Figure 3 – Single regression of equations 4 (a) and 5 (b).

According to the bibliographic study(2-8) about the coal substitution rate there is a natural tendency for the authors to adopt relations based on some parameters from preliminary analyses, physical and chemical characteristics of the coal used, and process data, specially the injection rate in the blast furnace. However, there is no single relation capable of describing and equate in a generalized form the substitution rate in terms of those parameters. Each industrial plant has its own particularities, and a judicious analysis is necessary to verify which variables are relevant to the process, in order to obtain the desired model.

It can be seen from the models presented for the substitution rate of the Usiminas BF 3 that their r^2, values are very close, in the order of 50%, which makes it possible to choose any one of them to be employed operationally, as shown in figure 4, where the industrially collected data are compared to the results from the models developed in this study. The correlation values of the non-linear models (equations 4 and 5), which are around 0.7, are appropriate in this statistical analysis.

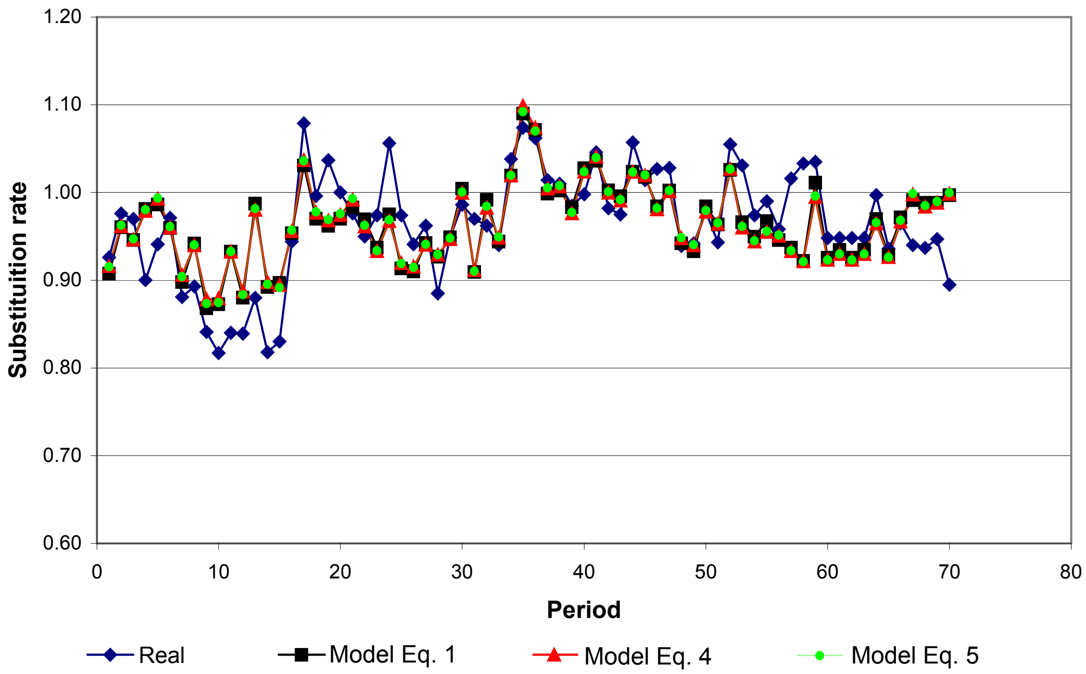

Figure 4 – Comparison between collected operational data (Real) and models developed for the BF 3 substitution rate (Model for equations 1, 4 and 5, respectively).

About at Figure 4, it can be verified that the models fitted very well to the actual data especially in the central area (period: 20-50) of the plot, where percent errors smaller than 1% were found between the model and the actual data. In some small regions the model showed some misfit, especially at the end (period: 60-70) where percent errors of up to 11.7% were verified.

3.3 Estimate of Fuel-rate Variation Resulting of a Change in the Injected Coal Type

Each coal has a specific calorific value and the higher this property, the lower is the amount of coal which must be injected for a determined blast furnace charge. For lower values, the injection rate must be raised in order to compensate for the drop in the calorific value, considering the same charge. Thus, the change of the coal or mixture to be injected in the tuyeres, changing the calorific value, causes a thermal variation in the blast furnace and the need to determine the amount of fuel (fuel-rate) to compensate for this variation.

A method used to quantify the variation in the fuel-rate as a function of the variation in the calorific value of the coal was suggested by *Nippon Steel Corporation*, which consists initially in plotting the substitution rate values as a function of the calorific values. After the linearization of the plotted data, a relation of the type $y = ax + b$ is found between the substitution rate and the calorific value. The inverse of the angular coefficient of this equation is the equivalent thermal input (energy removed or supplied) for each kg of fuel-rate.

The methodology used in this work yielded three equations (1, 4 and 5) for determining the substitution rate. For estimating the fuel-rate variation which results from the change of the coal type of mixture injected in the blast furnace tuyeres, equation 1 was used (substitution rate as a function of the carbon content and the injection rate, obtained by multiple regression). The substitution rate values obtained were then plotted as a function of the calorific value of the coal or mixture of coals used in the Usiminas BF 3, according to Figure 5 (a). The regression plot for the previous correlation is presented in Figure 6.

A low value of r^2 was found at the development of the equations for calculating the substitution rate. One of the reasons for this may be the long period of time used in the evaluations (September/02 till December/06), in which there is a marked variation of the blast furnace operational parameters, affecting each mean injection rate value. The correlation coefficient obtained by the single regression was of 0.67 which can be considered adequate for industrial data.

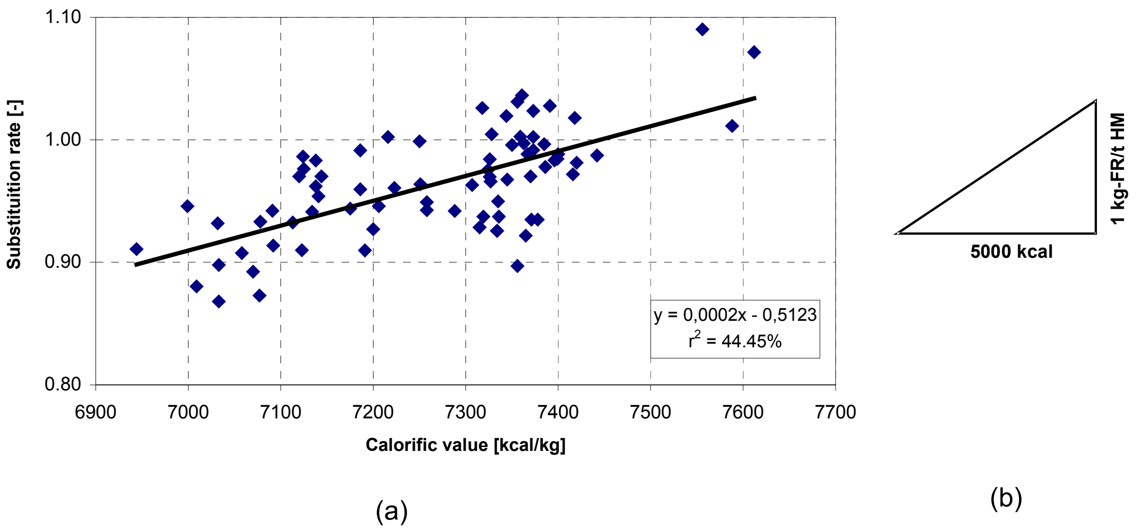

Figure 5 – Relation between the substitution rate and the calorific value (a) and heat input equivalent for each kg of fuel-rate (b).

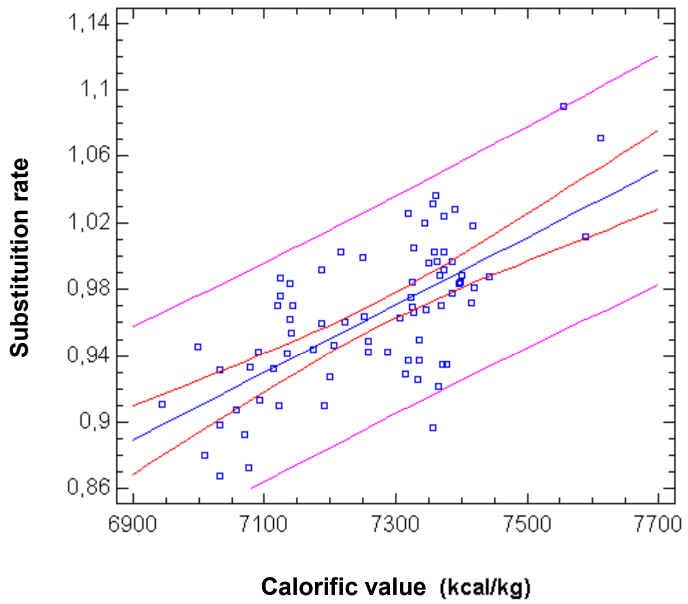

Figure 6 – Single regression of the substitution rate as a function of the calorific value.

The value found for the heat input equivalent was 5000 kcal for each kg of fuel-rate, as shown in Figure 5 (b). Considering, for example, an injection rate of 100 kg/tHM, when a coal with a calorific value of 7500 kcal/kg is replaced by another one with 7700 kcal/kg, the fuel-rate variation is of – 4 kg/tHM, which means that for the same charge, the injection rate can be reduced by 4 kg/tHM.

This correction of the fuel-rate (coke-rate) variation contributes to the stability of the process, since the changes of coal types or mixtures injected always result in larger or smaller operational variations of the blast furnace.

As a reference, the model presently used at the Usiminas blast furnaces for the estimation of the variation of the fuel-rate when the type of coal injected is changed is also presented. The model was suggested by Nippon Steel Corporation and shows an equivalence of 3600 kcal for each kg in the fuel-rate, based on own statistical analyses.

When a change of the coal (or mixture) injected is changed, a simulation is performed in order to estimate the variation on the fuel-rate (coke-rate). This simulation is based on the equivalence of 3600 kcal/kg for each kg in the fuel-rate and the results help the thermal control of the blast furnace.

An example is shown in Table 3, where the results of the simulation conducted for the replacement of the mixture of coals (A + B) by the mixture of coals (C + D) are presented. Based on the injection rates used at the blast furnaces, the calorific value of the mixture of coals and the equivalence of 3600 kcal/kg, an estimate of the fuel-rate variation can be obtained. In the present example, the calculations showed that a change of the coal mixtures has a relevant influence on the fuel-rate (fuel-rate reductions of around 7.0 kg/tHM in BF’s 1 and 2 and around 8.0 kg/tHM in BF 3). Therefore, previous changes in the blast furnaces are suggested, taking in account the results of the simulation and the thermal state of the furnace at the time of change (for example, a reduction in the fuel-rate of about 5.0 kg/t is suggested).

Table 3 – Calculation of the change of coals in the blast furnaces.

BF	Calorific value		PCR	Coke Rate Variation (kg/tHM)
	Present	New	(kg/tHM)	
1	7259	7461	120.0	**-6.714**
2	7259	7461	120.0	**-6.714**
3	7259	7461	140.0	**-7.833**

Coal	A	B	Present
%	57	43	Average
PCI	7417	7050	7259
C	8040	7510	78.12
H	290	354	3.18
O	496	815	6.33
N	177	180	1.78
S	51	62	0.56

Coal	C	D	New
%	40	60	Average
PCI	7241	7607	7461
C	7760	8170	80.06
H	322	343	3.35
O	621	420	5.00
N	186	177	1.81
S	61	59	0.60

4 CONCLUSION

In the present paper, operational data of Usiminas Blast Furnace No. 3 and coal for injection analyses were evaluated in the time from September 2002 till December 2006.

According to the literature, there is no single relation capable of describing and equate the coal substitution rate in a generalized way. Each industrial plant has its own particularities, demanding a judicious analysis to verify which variables are relevant to the process, so that the adequate model can be obtained. The most used parameters to describe the process are: injection rate in the blast furnace, carbon and oxygen contents, calorific value and percentage of volatile matter in the coal. The substitution rate is inversely proportional to the injection rate, the volatile matter and the oxygen content, and directly proportional to the carbon content and the calorific value.

Concerning the statistical analysis of the data collected, it was observed that statistically relevant variables for the modeling of the BF 3 substitution rate are the carbon content and the injection rate, the latter being strongly related to the dependent variable. Three equations were generated from these variables, and the correlation coefficients obtained for each one were approximately 0.7, considered adequate when using industrial data.

The estimation of the variation in the fuel-rate (coke-rate) resulting of changes in the type of coal injected in the blast furnace tuyeres is a auxiliary tool for blast furnaces experts decisions. It helps the continuous search for process stability and the maintenance of high productivity levels and high rates of fines injection, also contributing to the cost reduction of the production of pig iron.

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