BI-FACTORIAL ANALYSIS OF THE REDUCTION PROCESS IN IRON BLAST-FURNACES[1]

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bstract
The blast-furnace process is acknowledged as one of the most complex in metallurgy. The great number of thermo and fluid-dynamic phenomena occurring in the various zones in the reactor, mostly simultaneously, make the process extremely difficult to model. As consequence, the analysis of each factor contribution to the overall process is also complex. This paper propose a process analysis tool that segregates thermo and fluid dynamics factors leading to an clearer view of a particular operational regime. From those two factors, a series of secondary indexes allows the process analysis at various levels, according to the needs of operation and planning teams. The technique, its scientific background and its applications are presented and discussed in this technical contribution. Real data are analyzed and classified on its basis as result of the tool applicability.
Key words: Ironmaking; Blast furnace; Modeling.

ANALISE BIFATORIAL DO PROCESSO DE REDUÇÃO EM ALTO-FORNO SIDERUGICO

Resumo
O processo de redução em altos-fornos é reconhecidamente um dos mais complexos na indústria metalúrgica. O grande número de fenômenos termo-químicos que ocorre nas diversas zonas do reator, em muitos casos simultaneamente, torna o processo extremamente difícil de modelar. Como conseqüência, a análise da contribuição de cada fator para o desempenho do processo é também complexa. Este trabalho propõe uma ferramenta de análise do processo que permite segregar os fatores termoquímicos dos fluidodinâmicos facilitando a compreensão de um regime operativo em particular. A partir desses dois fatores, uma série de índices operacionais secundários permite análise em vários níveis de detalhes, de acordo com as necessidades da operação e no planejamento do processo. A técnica, seu embasamento científico e suas aplicações são apresentados e discutidos nesta contribuição técnica. Dados reais são analisados e classificados com base na ferramenta desenvolvida.
Palavras-chave: Siderurgia; Alto-forno; Modelo

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1 INTRODUCTION

At present many different models, indexes and concepts are being used to describe blast-furnaces performance both in terms of productivity and energy consumption. The involved phenomena have been intensively and extensively studied by now. On the other hand, the different aspects are always observed independently one from another. More comprehensive and rational ways of analyzing the process is long needed. A proposal presented in this paper is one of integrating same already known models in a new, straight-forward and useful way.

2 MODEL CONCEPT

Blast furnace productive is now most frequently referred to inner or work volume. Not long ago in Germany and Holland hearth cross section was preferred as dimension factor. Being the blast furnace a counter flow reactor the latter option is clearly the most appropriate. In fact the reason why the choice for the first option have not brought troubles to process analysts is shown in Figure 1 where it is clear the good correlation between the two dimensions existent for all blast furnace designs. In other words, statistically they are equivalent and can be used as one in practical terms.

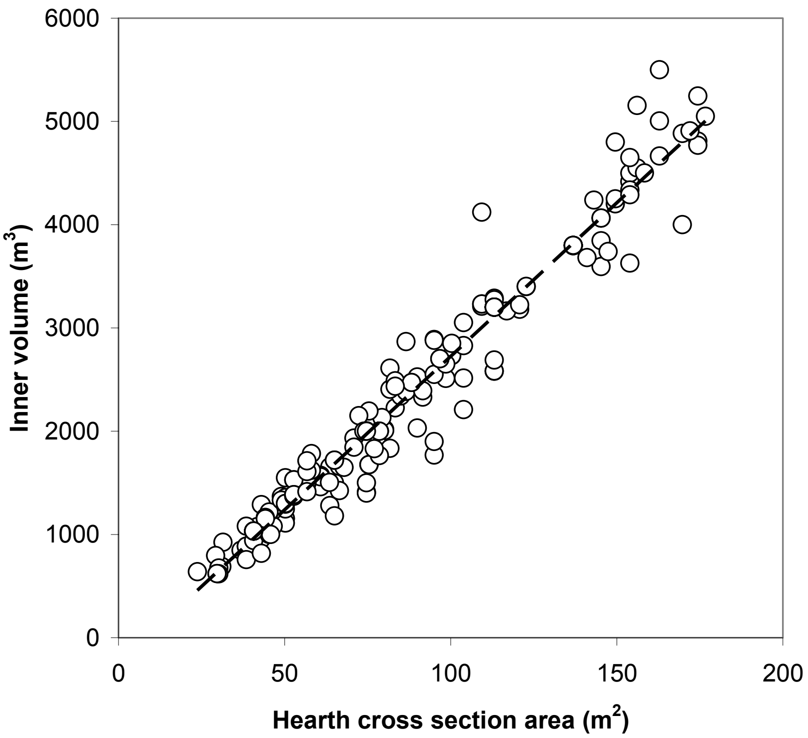

Figure 1 – Relationship between inner volume and hearth cross section to various blast-furnaces in the world.

To indicate permeability, or more correctly resistance to the gas flow, the Ergun[(1)] equation for porous beds

$$-\Delta P/\Delta z = 150\ (1 - \varepsilon)^2 \mu \,/\, g(\Phi d_p)^2 \varepsilon^3 \rho_g + 1{,}75\ (1 - \varepsilon) \,/\, g(\Phi d_p) \varepsilon^3 \rho_g G^2_g$$

was resolved for the blast furnace case with some assumptions and simplifications leading to

$$K = (Pb^2 - Pt^2) \,/\, \mathrm{V}tg^{\,1,7}$$

In Ergun original equation P, means total gas pressure, z vertical coordinate, ε void index, μ gas viscosity, g gravity factor, ρ_g gas density, Φ shape factor, d_p particles diameter and G mass gas velocity. In the applied and simplified version *Vtg* means tuyère gas flow, *Pb* absolute blast pressure, *Pt* absolute top pressure and k the flow resistance index.

Toxopeus(2) suggested the use of this equation to indicate productivity taking *Vtg* as the product of *P*, hot metal production rate, in t/day, times *Vsgt* , specific tuyère gas flow, in stpm3/t . This modifies the equation to

$$P = (Pb^2 - Pt)^{1/1,7} / K' \, Vstg.$$

In all cases stp stands for standard conditions of temperature and pressure.

To any blast furnace engineer it is reasonable to argue that the gas produced at the tuyère is not quite the one that crosses the most fluid-dynamically significant regions of the furnace. Again it is a matter of using a index that indicates the phenomenon but not as well as the proper one. The bosh gas volume, in other words, the one that crosses the thermal reserve is much closer to the volume of the gas that crosses the cohesive zone. That is the most significant one in terms of gas flow resistance, as well know. The reason for original option for the tuyère gas resides in the fact that necessary data have been more easily available. But for the other index that has became almost as easy although just a little more laborious as discussed presently.

It can recalled that μ, the carbon and hydrogen consumption index derived by Rist et al.(3) represent the number of kgmol C and H_2 based gas per kgmol of *Fe* in an particular blast furnace operation. If a new index ν, representing the number of N_2 kgmol per kgmol of Fe is added, $\mu + \nu$ represents the total number of gas to one kgmol of *Fe*. Now considering γ as the number of kgmol of *Fe* in one metric ton of hot metal $0{,}0224(\mu + \nu)\gamma$ would mean the specific bosh gas volume, in stp dam^3 t^{-1}, and can be calculated from simple operational data. The inverse of this expression, with the unit adjustment $(0{,}0224(\mu + \nu)\gamma)^{-1}$ can be called gas productivity, θ, with the dimensions t stpdam^{-3}.

To calculate μ, ν and γ a simple mass balance is need considering wind-rate, blast enrichment and humidity, fuel-rate and composition and hot metal carbon and iron content. Those data are easily available nowadays even in reports open to the general public.

The following equations can be used to the calculations needed

$$\mu\gamma = (CRxCc + IRxCi - 1000[C])/12 + IRxHi/2 + WRxWm/22{,}4/18000$$
$$\nu\gamma = WRxN_2w/22{,}4 + IRxNi/28$$

in which *CR* is the total coke-rate in kg per ton of hot metal, *Cc* the proportion of carbon in the coke, *IR* injection rate in kg/t, *Hi* is the hydrogen mass proportion in the injected fuel, *WR* is the total wind-rate in stpm^3 per ton per ton of hot metal, *Wu* is the blast moisture, in grams per stpm^3. N_2w is the proportion of nitrogen in the blast and *Ni* is the mass proportion of nitrogen in the inject fuel including carrier gas, if used. Notice that CO, CO_2, H_2 and H_2O are considered alike.

A new fluid-dynamic equation could be derives from the one presented above if a correlation between *Vtg*, tuyère gas flow, and *Vbg*, bosh gas flow. That can be obtained in two ways, statistical analysis of industrial dada and using a simulation model. Figure 2 shows the result of a statistical approach.

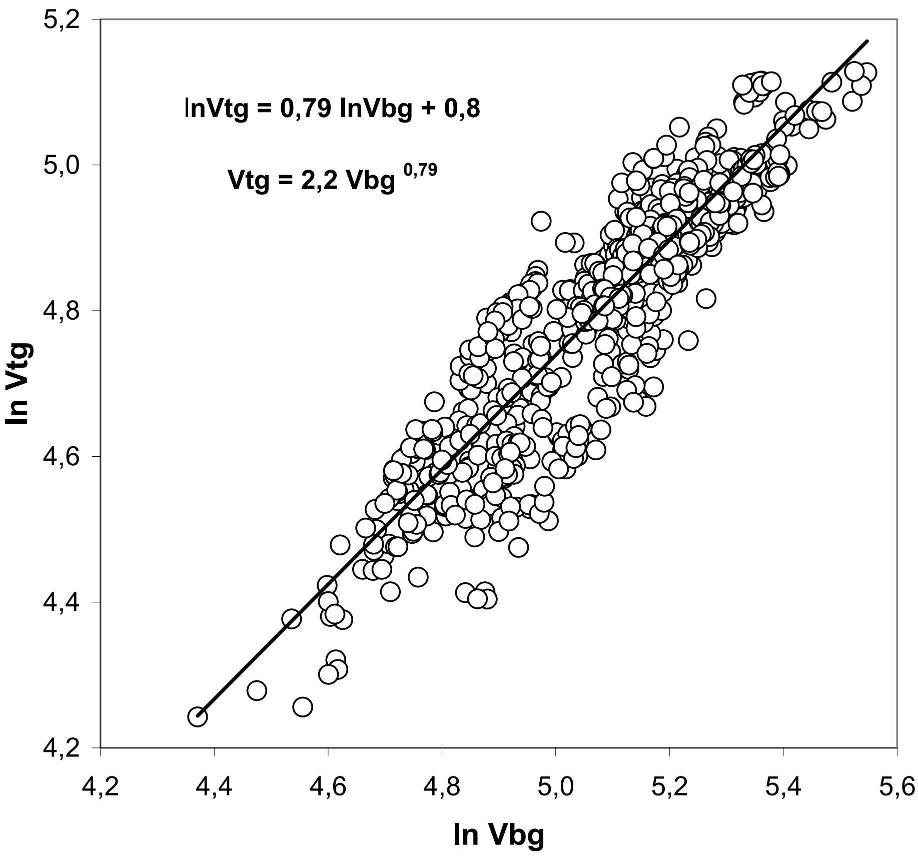

Figure 2 – Correlation and regression between tuyère gas and bosh as from industrial data.

With this result it is possible to rewrite the fluid-dynamic equation with the new gas index

$$K = (Pb^2 - Pt^2) / Vbg^{1,7x0,79}$$

And deriving a new productivity equation

$$P = (Pb^2 - Pt^2)^{0,74} / K''' \ Vsbg.$$

bearing in mind that the exponential number and the constant K were adjusted. It can be notice that $Vsbg^{-1}$ is in fact θ. If production rate is taken by the hearth cross section unity P, in t/day, can became π in $th^{-1}m^{-2}$, letting unities to be adjusted by K'''. What links π to θ is a relation between $(Pb^2 - Pt^2)^{0,74}$, a pressure differential and K''', a flow resistance index. If the first index is called δ and the latter ρ, and the relation between them called ϕ, clearly a gas flow index in $stpdam^3m^{-2}$, new equation arrives

$$\pi = \delta \rho^{-1} \theta \qquad or \qquad \pi = \phi \theta$$

The value of ρ indicates gas flux resistance.

This equation, that can be called the *pithetaphi* model, has many advantages in relation to the ones taken as starting point, among them, the possibility of comparing furnaces of different sizes.

3 RESULTS AND DISCUSSION

The authors consider that the relevant feature of this model its bi-factorial character. Quantifying ϕ and θ, the blast furnace analysts see a fluid-dynamic factor ϕ, and a thermo-dynamic one, θ. Both are important to productivity. Furnaces can have the same productivity having different combinations of the two factors allowing classify then as permeability efficient or thermally and chemically efficient. Figure 3 shows various results of furnaces all over the world to exemplify. A logarithmic plot is more convenient to observe the various operational stiles and performances.

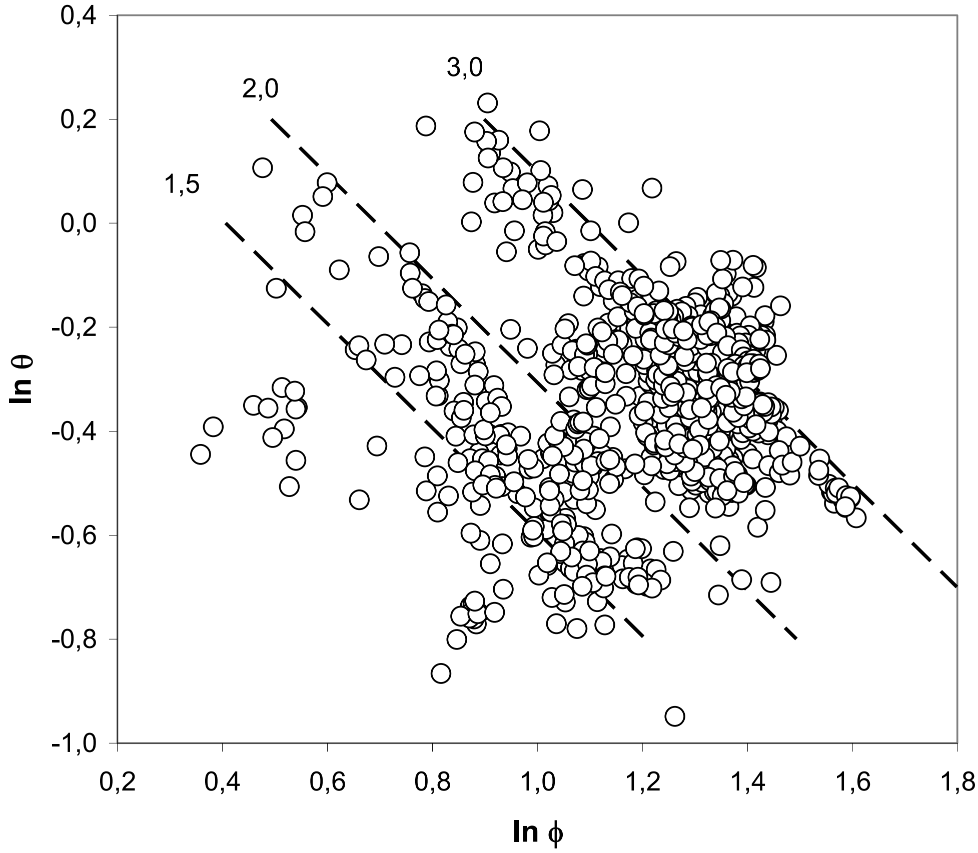

Figure 3 – Piphitheta model applied to various furnaces. Isometrics are plotted for π, in t $h^{-1}m^{-2}$

The use of t, metric ton, stp dam^3, cubic decameter in standard temperature and pressure, and hour proved to be much more convenient.
The analysis on the value of the index ρ, that can be held, for instance, with the aid of a artificial neural network can develop the produce an hybrid model.(4)

4 CONCLUSIONS

The proposed *piphitheta* bi-factorial model has many advantages in relation to the ones used so far by blast furnaces analysts. Among them, the possibility of comparing furnaces of different sizes and the possibility of quantifying a fluid-dynamic factor ϕ, and a thermo-chemical one, θ, for a particular operation.
Using t h^{-1} m^{-2} allows a more rational assessment of the process.
Further analysis can derive from research on the various factors related to the indexes μ and ρ, using for instance a neural network model.

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