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CARBON ESTIMATION OF STEEL IN A BOF WITH NOISE ATTENUATION

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Abstract: The estimation problem of carbon content of molten steel in a Basic Oxygen Furnace is addressed in this work. It is assumed that only measurements of carbon monoxide content of off-gas are available. Given that such measurements are corrupted with noise, determining the carbon from the thermodynamic equilibrium relationship yields poor results. Due to this, an integral estimator with noise attenuation is proposed. Results of numerical simulations show a good agreement between the actual carbon content and the estimated value. *Copyright © 2002 IFAC*

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1. INTRODUCTION

Undoubtedly, the basic oxygen furnace (BOF) steelmaking process is currently the world most important technology for producing raw steel. In the BOF process a supersonic oxygen jet is thrown on the surface of an iron bath in order to reduce by oxidation those impurities (carbon, silicon, manganese, phosphorus and sulphur) dissolved in the bath. Controlling carbon content is an important metallurgical task given that carbon determines the mechanical properties of steel. Despite BOF is considered a mature technology, some issues remain unsolved, e.g. the full automation of the process. One of the main factors which has prevented the full automation of the process is that associated with the difficulty to get on-line measurements of the main variables of the process, e.g. carbon content of the steel bath, due to the harsh and corrosive furnace environment, which prevents the employment of hard sensors. Due to this, frequently model-based controllers exhibit unsuccessful performance in industrial practice. The lack of continuous on-line measurements has motivated industrial researchers to use the off-gas composition as an indirect indicator of the bath carbon content. By employing thermodynamic principles, the bath carbon content can be calculated from the off-gas carbon monoxide (CO) content. Unfortunately, calculation of carbon content from thermodynamic considerations yields poor results when CO measurements are corrupted with noise. Currently, at least two commercial control systems based on off-gas analysis are available: the MEFCON system (Hahlin, 1993), and the DYNACON system (Schmidt *et al*., 2000).

In this work, a novel integral estimator proposed by Busawon and Kabore (2001) is designed in order to estimate the carbon content from noisy CO measurements. A mathematical model which considers two decarburization mechanisms is utilized. In the first mechanism (from 4.0 to 0.3 wt % C), decaburization rate depends on the oxygen flow rate, whereas in the second one (less than 0.3 wt % C), the mass transfer of carbon to the bath-oxygen interface determines the rate of carbon removal.

2. SYSTEM DESCRIPTION

The BOF steelmaking process is illustrated in Figure 1. The supersonic oxygen jet is thrown on the surface of the iron bath by means of a water-cooled lance. Dissolved carbon is oxidized to carbon monoxide and carbon dioxide; those gases together with iron oxide dust are expelled towards the furnace mouth. A gas analizer, located above the furnace mouth, takes a sample of the off-gas, filter it to remove the dust, analizes chemically the sample, and finally sends the noisy CO measurement to the process computer.

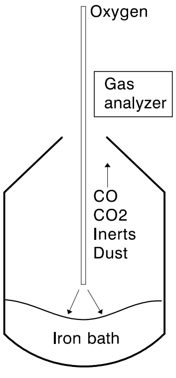

Figure 1. The BOF steelmaking process.

The following decarburization model was proposed by Chou *et al.* (1993). For carbon contents of iron bath greater than 0.3 wt% the decarburization rate is governed by the oxygen blow rate into the converter:

$$\frac{d[\%C]}{dt} = \frac{-Q_O(1-x_{in})^2}{18.7W_{hm}(1-0.5x_{CO}-x_{in})} \qquad (1)$$

where [%C] is carbon content of the metal bath, Q_O is blow-rate of oxygen, x_{in} and x_{CO} are the molar fractions of inert gas and carbon monoxide in the off-gas, respectively, W_{hm} is the weight of iron bath, and t is the time. Carbon monoxide is generated in the converter through the following chemical reaction: $[C]+\{CO_2\}\rightarrow 2\{CO\}$, whose equilibrium constant is expressed in this way: $K_1 = p_{CO}^2/(a_C p_{CO2})$, where p_{CO} and p_{CO2} are the partial pressures of CO and CO_2 in the off-gas, respectively, and a_C is the activity of carbon in the hot metal. Given that $p_{CO} = x_{CO}P$, $p_{CO2} = x_{CO2}P$, $a_C = f_C[\%C]$ and $x_{CO} + x_{CO2} + x_{in} = 1$, then the final expression for K_1 is: $K_1 = Px_{CO}^2/(f_c[\%C](1-x_{CO}-x_{in}))$. On the other hand, K_1 depends on temperature in this way: $K_1 = \exp(15.3 - 16759.0/T)$ (Chou *et al.*, 1993), then the carbon monoxide concentration in the off-gas can be estimated by solving this expression:

$$\frac{Px_{CO}^2}{f_C[\%C](1-x_{CO}-x_{in})} - \exp\left(15.3 - \frac{16759.0}{T}\right) = 0 \qquad (2)$$

In the above equations f_C is the activity coefficient of carbon and P is the off-gas pressure. The above authors, from data previously reported, derived by means of the least square method the following expression that takes into account the dependence of f_C on carbon content and temperature:

$$\begin{aligned}\log f_c &= 0.1666[\%C] - 0.01585[\%C]^2 + \\ &9.9613\bullet 10^{-7}[\%C]^3(T-273) + \\ &3.0246\bullet 10^{-5}[\%C](T-273)\end{aligned} \qquad (3)$$

On the other hand, for carbon contents less or equal than 0.3 wt%, the decarburization rate is controlled by mass transfer phenomena, i.e. transport of carbon to the bath-oxygen interface:

$$\frac{d[\%C]}{dt} = -\frac{k_d S[\%C]}{V} \qquad (4)$$

where k_d is the mass transfer coefficient, S is the bath-oxygen interface area, $V=W_{hm}/\rho$ is the melt volume, and ρ is the bath density. The bath-oxygen interface area can be estimated from the expression (Garnica *et al.*, 1994):

$$S = \frac{4}{3}\pi\, a\left[\left(\frac{L}{1000a} + \frac{1}{(2a)^2}\right)^{3/2} - \frac{1}{(2a)^3}\right] \qquad (5)$$

where L is the depth of the cavity caused by the supersonic oxygen jet, and a is the cavity shape factor. Besides, L depends on the lance height h, i.e. the gap between the bath surface and the nozzle tip, in this way (Garnica *et al.*, 1994):

$$L = L_0 \exp\left(\frac{-0.78h}{L_0}\right) \qquad (6)$$

where $L_0 = 63.0(60.0Q_O k/(nd))^{2/3}$. In this equation k is a coefficient according to the nozzle angle, n is the number of lance holes, and d is the diameter of the lance holes.

The thermal behavior of the steelmaking process is modeled by Chou *et al.* (1993) assuming that when scrap is added to the bath, the molten metal temperature follows a trajectory close and parallel to the liquidus line of the Fe-C phase diagram. Therefore

$$T = A - B[\%C] \qquad (7)$$

The above assumption is rather rough, however it can be improved in future works by replacing it with a formal heat balance in order to take into account the thermal contributions of silicon, manganese and phosphorus oxidation, and coolant and flux additions.

3. CARBON CONTENT FROM THERMODYNAMIC CONSIDERATIONS

A natural way for determining the carbon content of steel is using Eq. (2), which correlates the carbon content with CO content of off-gas assuming chemical equilibrium. This equilibrium is shown in Figure 2, using the parameter values considered in Table 1.

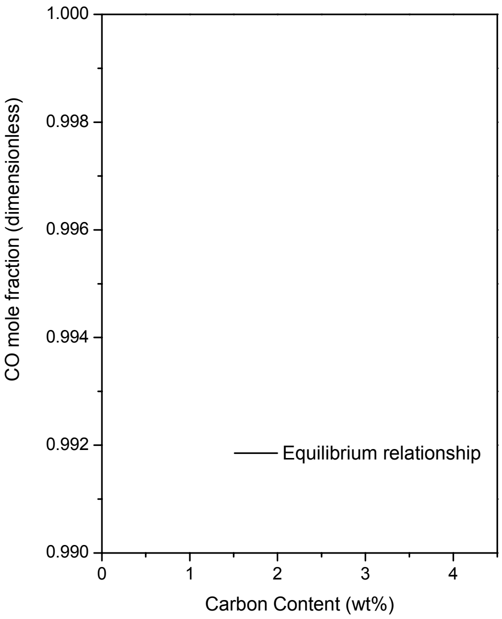

Fig. 2. Equilibrium relationship between the steel carbon content and the off-gas CO content.

From the above figure one can note that the carbon content is extremely sensitive to the CO content for carbon contents greater than 0.5 wt%. As the BOF behaves as a semi-batch reactor, industrial researchers are mainly interested in the final carbon content, which commonly is lower than 0.1 wt%. Frequently, CO measurements are corrupted with noise. This means that noise in CO measurements for carbon contents values lower than 0.5 wt% do not introduce a significant error in the carbon content estimation. However, for control purposes, it is mandatory to know precisely the steel carbon content at every moment during the oxygen blow. The effect of noisy CO measurements on the carbon content calculations using the equilibrium relationship is illustrated in Figure 3 for a typical blowing. The time scale for Figure 3 starts in t = 5 min because it is assumed that carbon oxidation initiates once the silicon in the bath has been depleted. In this figure a noise of 1% on the nominal value was supposed. An upper bound of 5 wt% was assumed for the carbon content, in order to reproduce a situation analogue to an industrial case. In Figure 3 the above remarks about the sensitive of the equilibrium relationship for carbon contents greater than 0.5 wt% are verified.

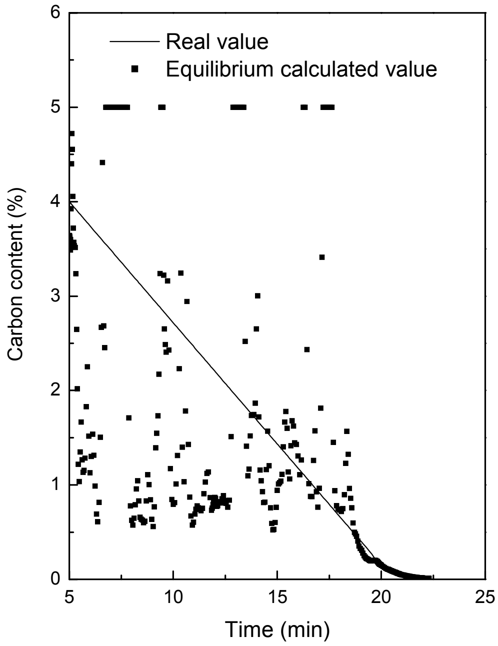

Fig. 3. Influence of noisy CO measurements on the calculated equilibrium carbon content.

Filtering of the results shown in Figure 3 are depicted in Figure 4. Here, a Fast Fourier Transform-based filter was used. From this figure it can be observed that employment of traditional filtering techniques yield unsatisfactory results.

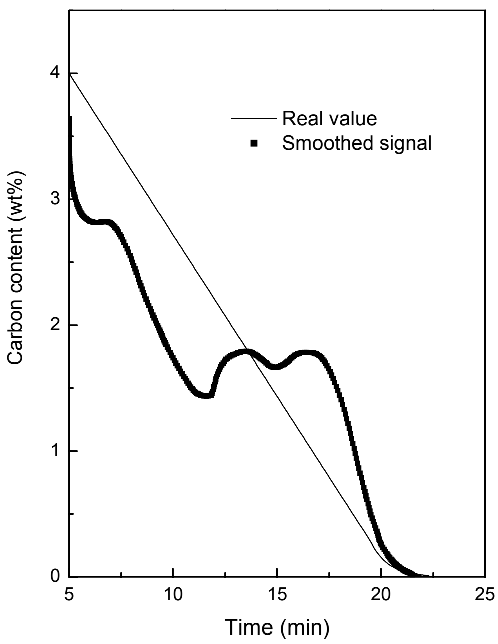

Fig. 4. Filtered values of the calculated equilibrium carbon content with noisy CO measurements.

4. CARBON CONTENT FROM STATE OBSERVERS

Considering the results shown in the previous section, it is clear that it is necessary to use another technique which allows to attenuate the adverse effects of noise in CO measurements. An alternative technique is the employment of state observers, which have been an important topic of research during the last decade because its particular importance in the design of controllers for systems with noisy measurements.

To design a state observer scheme for the steel carbon content from off-gas CO content, an explicit expression for the CO dynamics is needed. This expression is obtained by deriving Eq. (2), then the following equation is obtained:

$$\frac{dx_{CO}}{dt} = \frac{\frac{16759}{T^2}\left(\frac{(1-x_{CO})^2[\%C]f_c}{x_{CO}}\right)\exp\left(15.30-\frac{16759}{T}\right)\frac{dT}{dt} + x_{CO}(1-x_{CO})\left(\frac{\frac{d[\%C]}{dt}}{[\%C]}+\frac{\frac{df_c}{dt}}{f_c}\right)}{2-x_{CO}} \quad (8)$$

where df_c/dt and dT/dt can be obtained by deriving Eqs. (3) and (7) respectively. The decarburization rate in Eq. (8) is given by Eq. (1) whenever the carbon content of metal bath is greater than 0.3%, and by Eq. (4) otherwise.

Defining the system states as $z = [x_{CO}\ [\%C]]^T$, the BOF mathematical model can be expressed as follows:

$$\begin{aligned} \frac{dz_1}{dt} &= g_1(z_1, z_2) \\ \frac{dz_2}{dt} &= g_2(z_1, z_2) \end{aligned} \quad (9)$$

where the functionalities $g_1(z_1, z_2)$ and $g_2(z_1, z_2)$ are given by Eqs. (8) and (1) or (4) depending on the steel carbon content. Given that only measurements of off-gas CO content are available, the output for this system is $y = z_1 = x_{CO}$.

Using the above model, different state observers could be designed. The most common choice is the classical proportional integral observer (**PIO**) given as follows [Marino and Tomei, 1995]:

$$\begin{aligned} \frac{dw}{dt} &= y - \hat{z}_1 \\ \frac{d\hat{z}_1}{dt} &= g_1(\hat{z}_1, \hat{z}_2) + k_{P1}(y - \hat{z}_1) + k_{I1}w \\ \frac{d\hat{z}_2}{dt} &= g_2(\hat{z}_1, \hat{z}_2) + k_{P2}(y - \hat{z}_1) + k_{I2}w \end{aligned} \quad (10)$$

where $w, \hat{z}_1, \hat{z}_2$ are the observer states. Besides, $\hat{z}_1$ and $\hat{z}_2$ are estimates of the original states.

The constants k_P and k_I correspond to the proportional and integral gains of the observer, respectively. These gains are chosen such that the estimation error dynamics is stable.

Now, assume that the output measurements are corrupted with white noise δ. In this case, the **PIO** will not yield satisfactory performance given that if the proportional gain has a high value, then the noise will be amplified (Marino and Tomei, 1995). A similar reasoning applies for the integral contribution. To overcome these drawbacks, Busawon and Kabore (2001) proposed a new proportional integral observer. In their approach, the integral gain is used to stabilize the noise free estimation error dynamics, while the proportional gain is used to decouple the disturbance. Then, when modelling errors and sensor noise are present, the observer of Busawon and Kabore allows us to decouple completely the modelling uncertainties. Besides, the above authors showed that when only measurement noise is present, an integral observer (**IO**) is adequate to obtain good estimation capabilities. Then, given that in this work a perfect knowledge of the equilibrium relation and the parameters involved are assumed, an **IO** will be used to estimate the steel carbon content in the BOF from off-gas CO content.

To design the **IO** for system (9), a new state z_0 must be created. The augmented system is as follows:

$$\begin{aligned} \frac{dz_0}{dt} &= z_1 + \delta \\ \frac{dz_1}{dt} &= g_1(z_1, z_2) \\ \frac{dz_2}{dt} &= g_2(z_1, z_2) \end{aligned} \quad (11)$$

For the above system, a new output is defined as follows: $y_0 = z_0$. Note that this output is equal to the integral of the CO measured value.

Following Busawon and Kabore (2001), the **IO** for system (11) is given by:

$$\frac{d\hat{z}_0}{dt} = \hat{z}_1 + k_1(z_0 - \hat{z}_0)$$
$$\frac{d\hat{z}_1}{dt} = g_1(\hat{z}_1, \hat{z}_2) + k_2(z_0 - \hat{z}_0) \quad (12)$$
$$\frac{d\hat{z}_2}{dt} = g_2(\hat{z}_1, \hat{z}_2) + k_3(z_0 - \hat{z}_0)$$

where the gains of the observer k_1, k_2 and k_3 are constants whose values can be chosen such that the observer poles are all located at $-\lambda$, where λ is a positive constant.

For the sake of simplicity, the convergence proof of the **IO** can be found in Busawon and Kabore (2001). The noise filtering properties of the observer given by Eq. (12) will be illustrated in the next seccion by means of numerical simulations.

5. NUMERICAL EXAMPLE

Numerical simulations were carried out in order to test the predictive power of the considered estimation scheme. To evaluate this power, a comparision is made between the considered observer and the **PIO**. The gains of the **PIO** were chosen as follows: $k_{P1} = 2$, $k_{P2} = 1$, $k_{I1} = k_{I2} = 0$. This means that **PIO** is equivalent to a classical proportional observer. The integral gains was chosen null because modelling errors are not considered. The performance of both observers is depicted in Figure 5 using two sets of the **IO** observer gains.

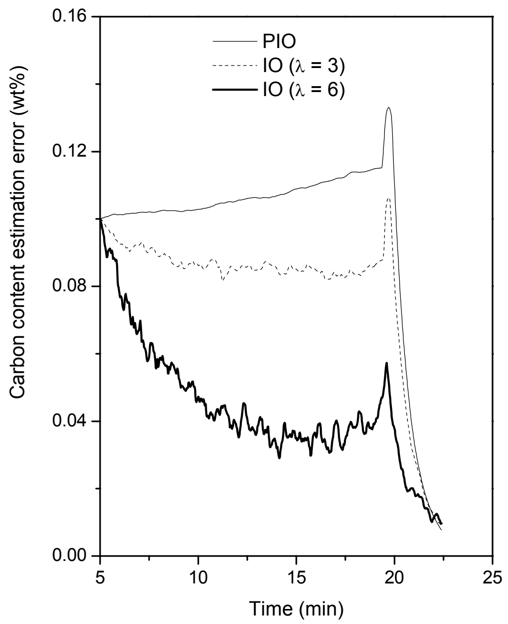

Fig.5. Comparision of estimators performance.

In the numerical simulations shown in this figure, an error equal to 0.1wt% in the initial carbon concentration estimate was assumed. The **PIO** poles were chosen equal to –1 because in accordance with computer simulations, for values lower than –1, this observer becomes unstable due to the noise presence. Then, the results for **PIO** presented in Figure 5 are the best that can be obtained. Note that the **IO** poles can be located far away from zero, which allows to increase the convergence speed and preserve its stability properties.

From the above figure one can observe that as λ is increased, the estimation error decreases. However, this situation promotes high frequency oscillations of the estimated carbon content due to noise recovering.

6. FUTURE WORK

Some issues must be addressed in a further work. For instance, a comparison of the dynamic performance between the proposed estimation scheme and classical estimators such as the extended Kalman filter. Besides, the robustness of the proposed estimator against model and parameter uncertainties must be investigated in order this estimator can be implemented at industry.

7. CONCLUSIONS

The employment of the equilibrium relationship between the steel carbon content and the off-gas CO content in a BOF yields poor predictions of carbon content for those cases in which the CO measurements are corrupted with noise. Classical filtering techniques, such as Fast Fourier Transform-based, do not produce satisfactory results. On the contrary, an integral observer, as the considered in this work gives results very similar to the real ones. Therefore, the integral observer could be employed with confidence as a soft sensor for the steel carbon content in the BOF, and in the synthesis of controllers for complete automation of the BOF.

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NOMENCLATURE

a	shape factor of the oxygen jet cavity
d	diameter of lance nozzle holes, mm
f_c	activity coefficient of carbon
h	lance height, mm
k	coefficient according to nozzle angle
k_d	mass transfer coefficient
L	depth of the oxygen jet cavity, mm
n	number of lance nozzle holes
P	pressure of off-gas, atm
Q_O	oxygen flow rate, Nm^3/min
S	surface of the oxygen jet cavity, m^2
t	time, min
T	bath temperature, °K
V	melt volume, m^3
W_{hm}	weight of hot metal, metric ton
x_{CO}	molar fraction of CO in off-gas
x_{in}	molar fraction of inerts in off-gas
[%C]	carbon content of steel, wt %

Table 1. Values of the process parameters

Parameter	Value
Oxygen blow rate, Q_O	380.0 Nm^3/min
Iron bath weight, W_{hm}	120.0 ton
Molar fraction of inert gas, x_{in}	0.0
Pressure of off-gas, P	1.0 atm
Bath density, ρ	7.1 ton/ m^3
Number of lance nozzle holes, n	3
Diameter of lance holes, d	43.0 mm
Shape factor, a	4.1632
Coefficient, k	1.2
Mass transfer coefficient, k_d	3.98 m/min
Constant A in Eq. (8)	1873.0
Constant B in Eq. (9)	50.0
Lance height, h	3.0 m