

# Model of Mixed Control for Carbon and Silicon in a Steel Converter

C. BLANCO and M. DÍAZ

Department of Chemical Engineering, University of Oviedo, 33071 Oviedo, Spain.

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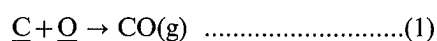
The removal of carbon in a steel converter has been studied under Gas–Liquid reaction considerations; diffusion and reaction parameters were determined and control regimes tested. Improvement of the prediction of C results in the end of the blowing process can be obtained considering the variation of factors during the process. This is also obtained by introducing the Si-removal in the simulation obtaining the C and Si evolution. Application to control is discussed in relation with the use of a slag reaction model.

**KEY WORDS:** Basic oxygen steelmaking; process control; mathematical model; end point carbon and silicon content; solubility of oxygen; oxygen consumption.

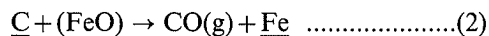
## 1. Introduction

In the steelmaking process of hot metal refining, the basic aim is the control of carbon levels that influence the final quality of the steel. Control of these carbon levels depends on our knowledge of the reaction mechanisms that operate in the process. Operating conditions in the converter make it difficult to determine the intermediate values of concentrations, and usually this concentration data is only available in the final moments of blowing. Therefore, we only have data at the initial and final times to contrast the validity of the model.

Removal of carbon has been analyzed<sup>1–3)</sup> in a simplified way by the equation:



However, other authors<sup>4)</sup> consider that this reaction takes place during the early stage of blowing, and is later the following reaction



which has the responsibility of eliminating carbon in the bath. The first reaction occurs at the gas/steel interface, while the latter occurs at the slag/steel interface and is a function of the quantity of FeO in slag. Because high temperatures favour the second reaction during the early stage, little removal takes place, but it increases during the process. Moreover, during the first moments the elimination of silicon, a very exothermic reaction, also occurs and the bath temperature increases.

Takawa *et al.*<sup>5)</sup> considered the oxygen blow as responsible for the oxidation of carbon, detecting two possible reaction mechanisms: a chemical control for the later stage of the process and a diffusional control in the first moments. Ghosh<sup>6,7)</sup> observed in Fe–C melts that at low oxygen pressures the rate of decarburization is a linear function of oxygen partial pressure and is in-

dependent of the flow rate, and that the absorption of oxygen in the bath is the controlling step; at high oxygen partial pressures, however the rate of decarburization is independent of the temperature and the process is controlled by the amount of oxygen blown. At the same time, for low carbon levels it is found that the rate of decarburization depends on the carbon content and the diffusion of carbon is the controlling mechanism. Ghosh and Sen<sup>8)</sup> showed that for carbon concentrations of 0.3–1.1% the controlling step is the reaction between the carbon and the absorbed oxygen. Wei and co-workers<sup>9)</sup> proposed as a mechanism that the C oxidation rate is proportional to the FeO concentration in the slag/metal interface in Fe–C–Si melts. This also agrees with the studies of Sommerville and co-workers.<sup>10)</sup> Surguchev *et al.*<sup>11)</sup> established that the carbon oxidation which occurs during the first stage is proportional to the oxygen and is independent of the carbon concentration, but that in the second stage it is proportional to the carbon concentration.

In this work, it is considered that carbon is eliminated by direct oxidation with the oxygen blown, and a correction for the oxygen used in the removal of silicon is added, which explains the final carbon levels from a steel plant.

Different mechanisms are considered to determine the model that can fit better the final data obtained in a LD converter. Here, we consider: 1) A simple mathematical model, combination of diffusional control due to the oxygen blown, and kinetic control due to the reaction between oxygen and carbon, 2) Corrections of the model of carbon, including the oxygen consumed by reaction with silicon, 3) The reaction of carbon with FeO of the slag controlled by mass transfer as a mechanism to fit the data obtained in the industrial plant.

## 2. Dynamic Model

The mass transfer equation for carbon results in

$$\frac{d(V\underline{C})}{dt} = \sum_j r_{cj}V + N_c A_c \quad \text{.....(3)}$$

where  $\underline{C}$  is carbon concentration in t/m<sup>3</sup> of hot metal,  $V$ : volume of hot metal m<sup>3</sup>,  $r_{cj}$ : carbon production rate by reaction  $j$ , and  $N_c A_c$ : the rate of carbon transfer to the slag phase per unit of time.

The evolution of carbon is going to be initially a function of the carbon removed through the fumes by direct reaction with the oxygen and the carbon transferred to the slag phase. The model proposed is developed according to the following simplifications:

- A complete mixing is supposed.
- All the carbon is removed through the fumes,  $N_c A_c = 0$ .
- No accumulation of oxygen exists, having been consumed in the decarburization.

$$N_{O_2} A_{O_2, z=0} = \sum_j V r_{cj} + \frac{\partial [O_2 V]}{\partial t} \quad \text{.....(4)}$$

$$\frac{\partial [O_2 V]}{\partial t} = 0 \quad \text{.....(5)}$$

- The volume of reaction remains constant. According to the previous simplifications, Eq. (3) is transformed into:

$$v N_{O_2} A_{O_2} = \sum_j r_{cj} = r_c \quad \text{.....(6)}$$

where  $v$  is the stoichiometry coefficient, resulting in

$$V \frac{d\underline{C}}{dt} = v N_{O_2} A_{O_2} \quad \text{.....(7)}$$

In the industry it is common to talk in terms of oxygen absorption efficiency,

$$v N_{O_2} A_{O_2} = \eta G \quad \text{.....(8)}$$

where  $G$  is the flow of oxygen blown, and  $\eta$  the industrial efficiency.

Kinetics of carbon reaction can be controlled by different mechanisms. If we consider that a diffusional or chemical control is possible, two possible alternatives can be proposed<sup>5)</sup>:

**For low carbon concentration:** Kinetic regime, control by chemical reaction

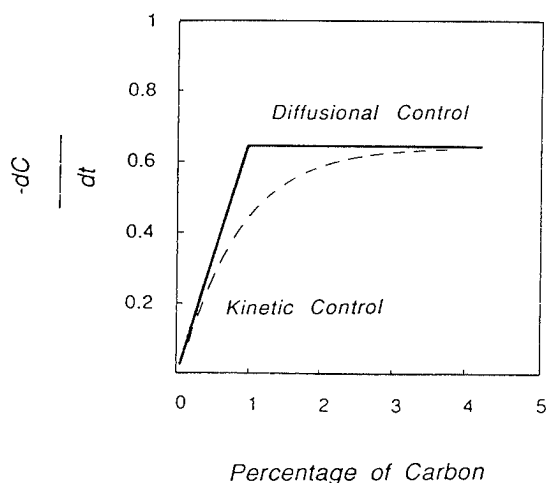


Fig. 1. Mechanisms of the carbon oxidation.

$$V r_c = V k' \underline{C} \quad \text{.....(9)}$$

where  $k'$  is the kinetic constant of reaction. This could take place in the last stage of blowing, where constriction equation for this regime (10) can be accomplished

$$\frac{\underline{C}}{v k_L A C_A^*} \ll \frac{1}{V k'}, \quad k^* = V k' \quad \text{.....(10)}$$

**When the carbon concentration is high:** Diffusional control regime can take place,

$$V r_c = v k_L A C_A^* \quad \text{.....(11)}$$

where  $A$  is the area of reaction, and  $C_A^*$  is the solubility of oxygen, diffusion solute in the steel. The required equation for this regime (12) is better fulfilled in the early stages of the process (see Fig. 1)

$$\frac{1}{V k'} \ll \frac{\underline{C}}{v k_L A C_A^*}, \quad k^* = \frac{v k_L A C_A^*}{\underline{C}} \quad \text{.....(12)}$$

Considering the participation of both control mechanisms, the observed rate:

$$V r_c = k^* \underline{C}, \quad k^* = \frac{1}{\frac{1}{V k'} + \frac{\underline{C}}{v k_L A C_A^*}} \quad \text{.....(13)}$$

then, carbon removal can also be expressed in terms of oxygen consumption:

$$W \frac{d\underline{C}'}{dt} = \frac{1}{\frac{1}{a \underline{C}'} + \frac{1}{b}} \frac{dO_{2 \text{ total}}}{dt} \quad \text{.....(14)}$$

where

$$a = \frac{V k' \rho}{G}, \quad b = \frac{v k_L A C_A^*}{G} \quad \text{.....(15)}$$

are respectively related with the kinetic constant of reaction and the oxygen coefficient transfer in the melt. Then, by integration:

$$W \int_{C_o}^{C_f} \left( \frac{1}{a \underline{C}'} + \frac{1}{b} \right) d\underline{C}' = \int_0^{O_{2 \text{ total}}} dO_2 \quad \text{.....(16)}$$

$$\frac{1}{a} \ln \frac{C_f'}{C_o'} + \frac{1}{b} (C_f' - C_o') = \frac{O_{2 \text{ total}}}{W} \quad \text{.....(17)}$$

### 3. Discussion of Results

#### (1) Coefficients for the Model

From Eq. (17), coefficients are obtained by fitting a total of 220 data of the process from the LD-III steelmaking of Ensidesa (Spain), using the initial and final carbon concentrations and the substance data, the mass of hot metal and the oxygen consumed in each operation. In Table 1 the characteristic parameters of operation and the obtained correlated coefficients ( $A'$  and  $B$ ) are shown.

$$A' = \frac{1}{a} = \frac{G}{V k' \rho}, \quad k' = \frac{G}{A' V \rho} \quad \text{.....(18)}$$

**Table 1.** Characteristic parameters used in prediction of the carbon profile using the model of mixed control.

Standard values used		
1.	$W$ = Additions + hot metal	
2.	$\langle W \rangle = 297.865 \text{ t}$	
3.	Mean oxygen blown = $G = 1.20 \text{ t/min}$	
4.	Mean density of the hot metal = $7.1 \text{ t/m}^3$	
5.	Volume of hot metal = $W/\rho$	
6.	$\langle V \rangle = 41.953 \text{ m}^3$	
7.	$A = 32 \text{ m}^2$	
8.	$v = 0.75$	
9.	$C_A^* = 0.0156 \text{ t O}_2/\text{m}^3$ hot metal = 0.22 %	
Fitting of carbon		
Dependent variable = $\text{O}_{2 \text{ total}}/W$		
Independent variable	Coefficient	$R^2$
$\ln(C_f/C_o)$	$A' = -0.000523$	0.9991
$C_f - C_o$	$B = -0.01244$	

$$B = \frac{\rho}{b \cdot 100} = \frac{G}{vk_L a_L V C_A^* \cdot 100}, \quad k_L a_L = \frac{G}{B v C_A^* \cdot 100 V} \quad \dots\dots\dots(19)$$

Using this mixed control model and considering the mean values for the oxygen flow, the mass and the volume of reaction, the kinetic constant and volumetric mass transfer coefficient will be  $k' = 7.70 \text{ min}^{-1}$ , and  $k_L a_L = 1.92 \text{ min}^{-1}$ . The  $k_L a_L$  value is well inside the range of mass transfer coefficients in Gas-Liquid (G-L) absorbers<sup>12)</sup> with the viscosity and surface tension properties existing in the converter.

## (2) Characterization of Regimes of Control<sup>12-14)</sup>

The industrial data were analyzed and it was assumed that if  $k' C' \ll vk_L a_L C_A^*$ , kinetic control exists and if  $vk_L a_L C_A^* \ll k' C'$ , diffusional control takes place. With an initial carbon concentration of 4.194 % and a final value of 0.047 %, the following results were obtained:

For **early stage**  $k' C' = 32.306 \text{ min}^{-1}$ , and  $vk_L a_L C_A^* = 0.316 \text{ min}^{-1}$  and therefore, diffusional control takes place. For the **last stage**,  $k' C' = 0.362 \text{ min}^{-1}$ , with the same  $vk_L a_L C_A^* = 0.316 \text{ min}^{-1}$  as we consider constant solubility and hydrodynamic conditions. In this case a combination of the two controls must be assumed.

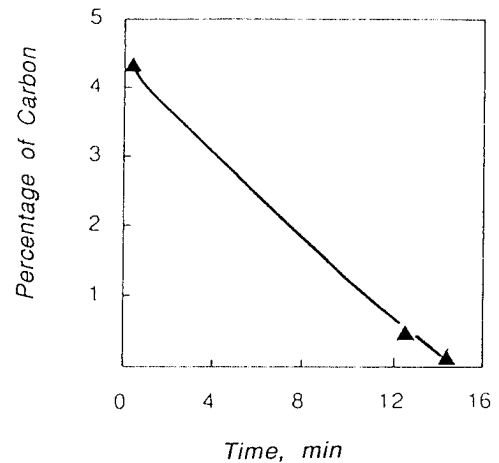
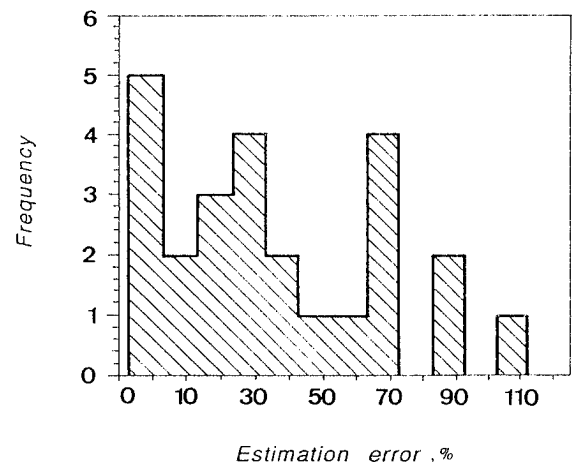
From the data used it is observed that during most of the decarburization process a diffusional control of oxygen towards the reaction phase exists. At the end of the process, the kinetic term becomes important due to the small amount of remaining carbon. The proposed model can be satisfactorily used in the analysis of industrial data.

## (3) Carbon Profile and Carbon Final Value Fitting

By integration of Eq. (14) with time:

$$\frac{1}{vk_L a_L C_A^*} \underline{C}_o' + \frac{1}{k'} \ln \underline{C}_o' = t + \frac{1}{k'} \ln \underline{C}_f' + \frac{1}{vk_L a_L C_A^*} \underline{C}_f' \quad \dots\dots\dots(20)$$

If we consider  $\underline{C}_o' = 4.410 \%$ ,  $\text{O}_{2 \text{ total}} = 16.70 \text{ t}$ , 15 min time and the obtained coefficient from the model, the carbon profile evolution is obtained as shown in **Fig. 2**. The  $C_f$  obtained from the model at the final time is 0.033 %, while the experimental value observed in the


**Fig. 2.** Profile of carbon obtained using the model of mixed control.

**Fig. 3.** Distribution of errors observed in determination of final carbon according to the model of mixed control.

industrial plant, with the same raw material and conditions is 0.037, giving an error of 11 %. The validity of the model must be tested from the distribution of errors, because no intermediate data are available. This is shown in **Fig. 3**. Testing 30 data at random, an average error of the order of about 50 % was obtained.

The reason for the errors are: 1. We consider that all the carbon is eliminated by direct oxidation to the blown oxygen, and oxygen is only spent for C-removal. 2. Blown strategies, different additions (scrap,  $\text{Fe}_2\text{O}_3 \dots$ ) and operating conditions (lance height, operation time...) are not taken into account, even though some values such as the oxygen solubility  $C_A^*$  has been assumed constant.

To improve this model, two types of solutions are here proposed: firstly, to consider that  $C_A^*$  depends on steel concentration and, secondly, to introduce a correction for the oxygen consumed by the silicon removal.

## (4) Correction of the Model by Considering Oxygen Solubility as a Function of Steel Concentration

The use of the previous model of mixed control to determine the final carbon leads to errors in this determination as some of the parameters change in each operation and this has not been taken into account. Analyzing Eq. (17), a parameter like the solubility of

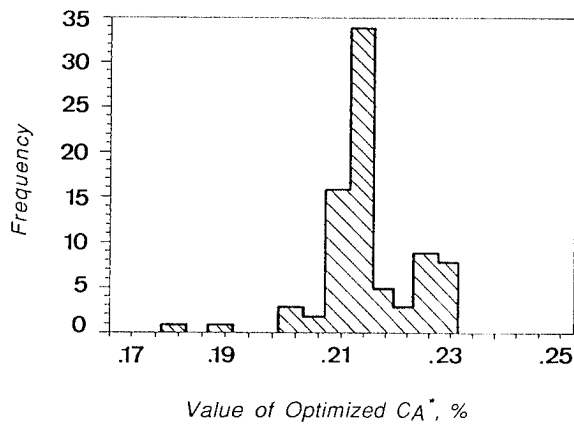


Fig. 4. Frequency of the value  $C_A^*$  of the optimized solubility of oxygen.

Table 2. Parameters for the fitting of the oxygen solubility. ( $r^2 = 0.999$ )

Dependent variable	$C_A^*$
Independent variable	Coefficient
$Si_o$	0.005
$S_o$	0.734
$S_o^2$	20.262
$C_o^2$	0.006
$Mn_o$	-0.118
$Mn_o^2$	0.091
$O_{2\text{ total}}$	$-59E-6$
$O_{2\text{ total}}^2$	$23E-11$
$t$	0.014
$W$	0.005
$W^2$	$-8.8E-6$

oxygen was estimated to be 0.22% in accordance with the data collected in the bibliography,<sup>15)</sup> but this solubility is neither constant along the whole time of reaction, nor the same for each operation as its value depends on the initial conditions of operation. The proposal is to use Eq. (20) assuming that the constants of the system (kinetic constant and transport coefficient) are those of the previous model, and to fit the value of the mean solubility in each operation to the initial conditions.

The solubilities for each operation have been optimized in order to obtain the minimum error in the final carbon determination. Very good results were obtained as the solubilities vary closely around the 0.21% of concentration. The reason is that concentrations in the converter and the operating conditions hardly change from one operation to another. In Fig. 4 the frequencies of the optimized solubilities are shown. The error obtained using these solubilities in the determination of the final carbon is about 4%.

Once the optimum solubilities had been calculated, these values were fitted to the parameters, of each operation. Solubility depends on the composition of hot metal, concentration of carbon, silicon, sulphur and manganese, total oxygen blown, mass of reaction and, finally, on the total time of blowing. A linear equation was proposed:

$$\text{Solubility} = \sum \text{Coefficient} \times \text{Independent variable} \dots (21)$$

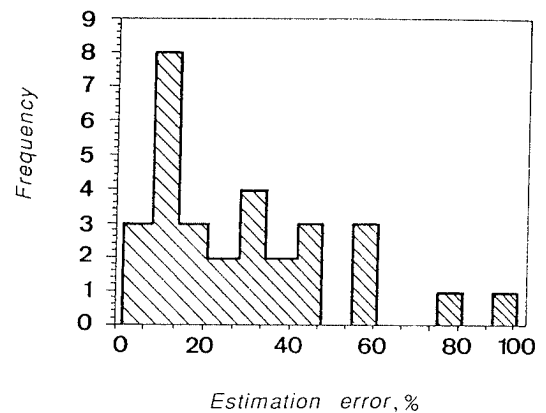


Fig. 5. Distribution of errors for determination of the final carbon, using the corrected model of mixed control.

The optimal coefficients of this equation obtained from the industrial processes are shown in Table 2.

Then, solubility of oxygen obtained from Eq. (21) with parameters of Table 2 can be introduced into the model (20), substituting the previous constant value 0.22%, and the final carbon can be predicted for each operation. A total of 30 data from the steelmaking were tested, and a mean error of 23% was obtained. In Fig. 5 is shown the distribution of errors. The interest of this results, is that this analytical method can be applied for models of control in practice and these models may include more independent variables. The aim can be to avoid the substance sampling.

#### 4. Correction of Silicon

Silicon reacts with oxygen to form  $SiO_2$  that later will be fixed by the CaO of slag. The reaction of silicon is very rapid, and practically all of it is removed during the first minutes of reaction. When oxygen bubbles enter the hot metal bath, which contains silicon and is at a temperature below 1400°C, the tendency for oxidation of the silicon is marked<sup>2)</sup> and direct oxidation is not difficult from the beginning of blowing. But, when the temperature increases to above 1500°C with a carbon content which is still significant (on the order of 3%), the rate of direct desilication decreases from a certain silicon content as a function of the temperature, although the reaction continues in the slag-metal interface, which decreases the speed of its development. The fact that silicon oxidizes with great speed does not exclude a certain simultaneous oxidation of carbon, although it is oxidized much faster with higher temperature and smaller silicon concentration.

As an approximation from the previous discussion and using results from the literature,<sup>16)</sup> we will consider that during the first two minutes total removal of silicon will take place, using a similar mechanism to the one of carbon in the previous chapter and assuming that during this period there will be practically no elimination of carbon.

Reaction taking place is supposed to be



starting from an equation of adjustment similar to that

**Table 3.** Fitting of the corrected carbon model for different consumptions of oxygen.

Time (min)	3-I Complete model		3-II Corrected model	
	$\frac{1}{a} \ln \left( \frac{\text{Si}'_f}{\text{Si}'_o} \right) + \frac{1}{b} (\text{Si}'_f - \text{Si}'_o) = \frac{\text{O}_{2 \text{ total}}}{W}$		$\frac{1}{b} (\text{Si}'_f - \text{Si}'_o) = \frac{\text{O}_{2 \text{ total}}}{W}$	
	1/a	1/b	1/a	$k_L a$
1	-0.0009	0.0012	-0.0060	3.353
3	-0.0030	0.0038	-0.0180	1.122
7	-0.0050	0.0063	-0.0290	0.713
13	-0.0110	0.0130	-0.0716	0.284
14	-0.0120	0.0145	-0.0740	0.275
Total	-0.0133	0.0140	-0.0850	0.239

of carbon, that is to say, taking into account a model of reaction-diffusion mixed control.

$$\frac{1}{a} \ln \frac{\text{Si}'_f}{\text{Si}'_o} + \frac{1}{b} (\text{Si}'_f - \text{Si}'_o) = \frac{\text{O}_{2 \text{ total}}}{W} \quad \text{.....(23)}$$

The adjustment of the equation is made in relation to the oxygen blown and % of the existent silicon, obtaining the value of 1/a and 1/b as previously with carbon. In Table 3-I is shown the adjustments with the different consumptions of oxygen that correspond to the different periods of blowing. From these, we can obtain the value of the oxygen mass transfer coefficient, which must be analogous to that of the reaction of carbon. We will assume that the elimination of silicon ends when the oxygen consumed has a transfer coefficient with the same value as that for carbon.

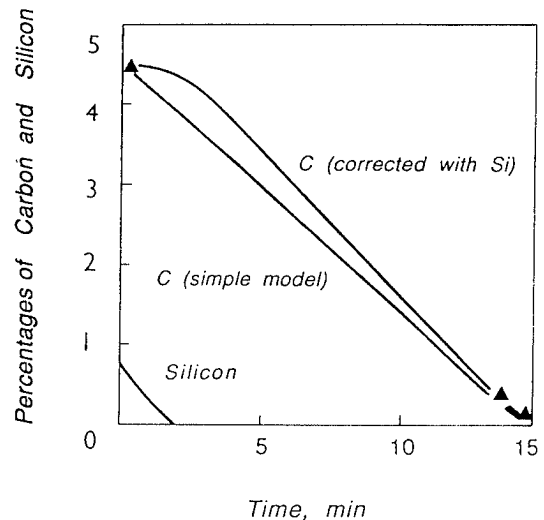
It can be observed that some of the constants in Table 3-I have positive values in the adjustments, that are incompatible with the proposed model. A new model was therefore developed for silicon, considering as a control mechanism the difficulty of oxygen to diffuse compared with the fast reaction of silicon. Again, the fittings are made considering this mechanism, for different consumptions of oxygen, and are reflected in Table 3-II obtaining the values of  $k_L a$ .

We can use the previous results to evaluate the silicon trajectory during the blowing (see Fig. 6), and also to correct the carbon model (Eq. (17)), by considering in this case the oxygen that is going to be used in the oxidation of silicon and obtaining the adjustment data. The new values of  $A'$  and  $B$  for the carbon model corrected by Si are:  $A' = -0.000867$  and  $B = -0.011194$ . Then,  $C_A^* = 0.22\%$ , and the constants obtained are  $k' = 4.64 \text{ min}^{-1}$  and  $k_L a_L = 2.26 \text{ min}^{-1}$ . Discussions on the controlling regimes do not change too much with respect to the C-model without Si-correction.

Considering again the data from Table 3, the value of  $k_L a_L = 2.26 \text{ min}^{-1}$  corresponds to the time of oxygen blown between one and four minutes from the start of blowing. By interpolation we find that silicon is practically consumed at the end of the third minute from the start of operation.

The trajectory of the silicon can be obtained from the model developed with diffusional control

$$-W \frac{d\text{Si}'}{dt} = \frac{v k_L A C_A^*}{G} \frac{d\text{O}_2}{dt}, \quad \text{and} \quad \text{.....(24)}$$


**Fig. 6.** Evolution of silicon and carbon with and without Si removal considerations.

$$\frac{\text{O}_{2 \text{ total}}}{W} = - \frac{G}{100 v k_L a_L C_A^* V} (\text{Si}'_f - \text{Si}'_o) \quad \text{.....(25)}$$

In Fig. 6 we have presented two models for the determination of carbon: one of mixed control for carbon, and the other with a correction of silicon, and also the profile of silicon which is obtained using Eq. (24) or Eq. (25).

## 5. Comparison with a Mechanism Based on Reaction with Slag

We will consider the reaction (2)  $\text{C} + (\text{FeO}) \rightarrow \text{CO} + \text{Fe}$  for the removal of carbon. The proposed model can be useful to determine which is going to be the final carbon in the refining process, as determined from the error distribution results. Nevertheless, this method can have additional problems if implemented in control because it can be more easily act on the gas flow rate if this factor affects the Gas-Liquid reaction than on the characteristics of the slag if this was the controlling process assumed. If reaction in the steel phase is considered as an irreversible instantaneous reaction in the steel-slag interface, the rate of C-removal in this case can be expressed as<sup>17)</sup>:

$$R_{\text{FeO}} = k_{L\text{FeO}} \text{FeO}^* \left[ 1 + \frac{\mathcal{D}_C \text{C}}{\mathcal{D}_{\text{FeO}} \text{FeO}^*} \right] \quad \text{.....(26)}$$

This equation is simplified depending on whether  $\mathcal{D}_{\text{FeO}}\text{FeO}^*$  is higher or lower than  $\mathcal{D}_{\text{C}}\underline{\text{C}}$ . As the percentage of carbon in hot metal is high, we assume that it takes place in the first of the proposed situations

$$R_{\text{FeO}} = k_{\text{LFeO}} \frac{\mathcal{D}_{\text{C}}}{\mathcal{D}_{\text{FeO}}} \underline{\text{C}} = R_{\text{C}}, \quad \text{and} \quad \dots\dots\dots(27)$$

$$-\frac{d\underline{\text{C}}}{dt} = k_{\text{LFeO}} a_{\text{S}} \frac{\mathcal{D}_{\text{C}}}{\mathcal{D}_{\text{FeO}}} \underline{\text{C}} = k'_{\text{L}} a_{\text{S}} \underline{\text{C}},$$

$$k'_{\text{L}} a_{\text{S}} = k_{\text{LFeO}} a_{\text{S}} \frac{\mathcal{D}_{\text{C}}}{\mathcal{D}_{\text{FeO}}} \quad \dots\dots\dots(28)$$

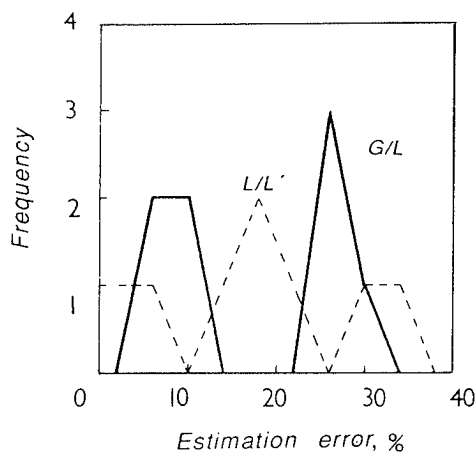
Using the experimental data from steelmaking we can test this equation to predict the adequate evolution of carbon and mainly the results in the final times of the process. In order to achieve this, it is necessary to determine what the value of  $k'_{\text{L}} a_{\text{S}}$  should be to fit the final carbon values to those of the process.

The  $k'_{\text{L}} a_{\text{S}}$  coefficient has been adjusted using results from the industrial plant. The average  $k'_{\text{L}} a_{\text{S}}$  value is  $0.299 \text{ min}^{-1}$ . Nevertheless, this  $k'_{\text{L}} a_{\text{S}}$  coefficient changes with  $\text{Si}_0$ ,  $\text{Mn}_0$  concentration (also, the oxygen supplied) and the raw material used, mainly that forming slag, which makes it more difficult to use this method.

An additional and also more empirical and refined treatment involves the fitting of this  $k'_{\text{L}} a_{\text{S}}$  value to a linear equation with the important variables mentioned. Parameters and variables treated are shown in **Table 4**. This new approach can be used, then, to identify errors

**Table 4.** Fitting of the mass transfer coefficient  $k'_{\text{L}} a_{\text{S}}$ . ( $r^2 = 0.9970$ )

Dependent variable	$k'_{\text{L}} a_{\text{S}}$
Independent variable	Coefficient
$\text{Si}_0$	0.1541
$\text{Mn}_0$	-0.0724
Hot metal	0.0014
Scrap	0.0022
Dolomite C	-0.0316
$\text{O}_2$ , $t = 2-4 \text{ min}$	$940E-7$
$\text{O}_2$ , $t = 4-7 \text{ min}$	$-195E-6$
$\text{O}_2$ , $t = 7-13 \text{ min}$	$120E-7$
$\text{O}_2$ , $t = 14 \text{ min}$	$802E-8$



**Fig. 7.** Comparison between errors obtained with different methods: gas/steel (G/L) reaction and steel/steel/slag (L/L) reaction.

in the final determination of carbon present in the converter for a total of 63 data from the steelmaking plant.

Finally, comparison of the error distribution with this empirical model of reaction in the slag and the model of Gas/Liquid reaction corrected with silicon removal is shown in **Fig. 7**.

## 6. Conclusions

Although carbon removal is controlled by diffusion in the first stages a combination of this control with a chemical reaction control is needed to explain carbon removal in the last stages of blowing. Mass transfer and kinetic constants for the reaction are obtained and can be used to evaluate the carbon evolution in the converter. Results show that conditions for the proposed regimes of reaction are fulfilled. Because no intermediate data are available, the predictions of the model could only be tested with a large number of the results in the last minutes of blowing.

The model can also be improved by considering modification of the variables through the process, or between different processes as was done with the oxygen solubility. This strategy can be interesting for control operation aims. The model was improved also through removal of the silicon during the blowing. Profiles of carbon and silicon were obtained.

Models based on reaction in the slag can also be used for control application, although the action in the control can be more difficult to anticipate.

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## Nomenclature

- $a, b$ : Coefficients
- $a_{\text{L}}$ : Specific area of steel/gas relative to steel volume ( $\text{m}^{-1}$ )
- $a_{\text{S}}$ : Specific area of steel/slag relative to steel volume ( $\text{m}^{-1}$ )
- $A$ : Reaction interfacial area gas/liquid ( $\text{m}^2$ )
- $A', B$ : Coefficients
- $C_{\text{A}}^*$ : Solubility of oxygen in the steel ( $\text{t/m}^3$ )
- $C_{\text{A}}^*$ : Solubility of oxygen in the steel (%)
- $G$ : Flow of oxygen ( $\text{t/min}$ )
- $k_{\text{L}}$ : Mass transfer coefficient in gas/steel interface ( $\text{m/min}$ )
- $k'_{\text{L}}$ : Mass transfer coefficient in steel/slag interface ( $\text{m/min}$ )
- $k'$ : Kinetic constant ( $\text{min}^{-1}$ )
- $N_{\text{x}} A_{\text{x}}$ : Rate of transfer of  $x$  ( $\text{t/min}$ )
- $r_{\text{c}}$ : Global carbon reaction rate ( $\text{t/min m}^3$ )
- $r_{\text{c}j}$ : Carbon reaction rate by  $j$  mechanism ( $\text{t/min m}^3$ )
- $R_{\text{x}}$ : Velocity of reaction ( $\text{t/m}^2 \text{min}$ )
- $t$ : Time of reaction ( $\text{min}$ )
- $V$ : Reaction volume ( $\text{m}^3$ )
- $\langle V \rangle$ : Average volume of reaction ( $\text{m}^3$ )

$W$ : Reaction mass (t)  
 $\langle W \rangle$ : Average reaction mass (t)  
 $\underline{X}$ : Concentration of element in the steel phase (t/m<sup>3</sup>)  
 $\underline{X}'$ : Concentration of element in the steel phase (%)  
 $(X)$ : Concentration of element in the slag phase (t/m<sup>3</sup>)  
 $z$ : Distance from the gas-liquid interface  
 $\mathcal{D}$ : Diffusivity of reactant (m<sup>2</sup>/min)  
 $\nu$ : Stoichiometry coefficient  
 $\rho$ : Density of the reaction mass (t/m<sup>3</sup>)  
 $\eta$ : Industrial efficiency (%)

#### Subscripts

$o$ : Initial concentration  
 $f$ : Final concentration  
 FeO, C: Iron oxide, carbon  
 $L, L'$ : Steel, slag phases

#### Superscripts

\*: Concentration at interface (t/m<sup>3</sup>)

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