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APPLYING ESTIMATORS IN THE OPERATION AND CONTROL OF FESI FURNACES

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ABSTRACT

It is difficult to control the production of FeSi alloys and keep the process *"under control"*. This is partly due to insufficient measurements of important furnace hearth variables. Therefore, the metallurgist is executing the metallurgical control based on his furnace evaluation. Thus, the metallurgical control problem of FeSi furnaces is actually an *identification* problem, since furnace variables needed to control the process satisfactorily can not be measured. In this paper we discuss how the information from the furnace hearth can be improved by applying model based estimators and various tools in furnace evaluation. In turn, the achieved process information will form a basis for improved furnace operation and control.

INTRODUCTION

The production of FeSi alloys in submerged-arc furnaces consumes large amounts of electric energy. The daily production of 75 % FeSi in a 40 MW furnace is about 120 tonnes. An optimal furnace operation corresponds to a specific energy consumption of 8.0 MWh/MT, but the figure can easily reach 10 MWh/MT at poor operation. Hence, the economic potential of good furnace performance is considerable. However, experience tells us that the process is quite difficult to control, and continuous optimal furnace conditions seem hard to obtain. The control task of FeSi furnaces could be divided in two: The electrical control, being a fundamental basis for the rest of the process [1, 2], and the metallurgical control of the chemical reactions in the furnace by adjusting the feed composition and the electrical working-point [1, 3]. Presently, due to insufficient measurements the metallurgical control is manual and is executed by the metallurgist based on his process knowledge and furnace evaluation.

CHARACTERISTICS OF FESI FURNACE OPERATION

The process dynamics of a FeSi furnace are spread over a wide range of time. The active furnace dynamics include high frequency arcing dynamics with time constants below 1 ms, as well as the dynamics of the chemical reaction patterns with time constant of several days. Moreover, the cyclic furnace operations and control activities involve time delays of several hours [1, 4].

One of the main reasons for not obtaining steady furnace performance is insufficient information about the furnace condition. There are no direct measurements of the inner furnace conditions, and there is significant uncertainty regarding the properties of the raw material we add to the furnace. As a result of this an important task for the metallurgists is to determine the furnace condition by using observations and the available measurements.

Evaluation of furnace condition

The complex reaction patterns in the furnace, together with the wide-ranged process dynamics and the significant time delays connected with furnace operations, makes it difficult to evaluate the furnace condition. Evaluations based on instant observations and measurements may fail to indicate the furnace conditions, because the lengths of important dynamics exceed the time horizon of the observations and the lengths of the operator shift periods. Therefore, an operator will have difficulties in deciding the correct furnace conditions, because what he really observes on the furnace, is not necessarily a result of his own actions, but more likely the result of actions from the last shift or before. The same dilemma is present when evaluating the carbon balance of the furnace. When the metallurgist observes a change on the furnace, is it a reflection of an actual change in the furnace carbon balance, or is it the response of an alteration in the raw material composition he did several days ago?

To obtain more correct and consistent furnace evaluations we have to introduce tools that the operators and metallurgists can use to determine the furnace condition, and where the effects of different process dynamics can be taken into account. Examples of tools to use when analyzing measurement trends are filtering, correlation analysis, spectrum analysis and time series modelling. Today, measurement data analysis has become an important tool in furnace evaluation in Elkem, but the most important tool is still visual evaluation [4, 5].

Moreover, ways have to be found to increase the information from the furnace hearth. In Elkem we have focused on three different method developments: Model based estimators, simulation models and decision support systems (expert systems). The model development covers a stoichiometric and a dynamic model of the (Fe)Si process [6, 7, 8], and an expert system for FeSi furnace operation has been developed [4].

A new concept for furnace operation and control

In Elkem we are developing a "new concept" for furnace operation and control [5]. The main objective in this work is to improve process information level presented to the operators and metallurgists. Systematic furnace evaluation, decision support systems, simulation models and model based estimators are important parts in this new concept. We also concentrate on improving the electrical and metallurgical control strategies. FIG. 1 illustrates the new concept for furnace operation and control.

Model based estimators

It is a fact that the information needed to evaluate the furnace condition properly, is lacking. Moreover, the insufficient instrumentation level obstructs the development of reliable automatic metallurgical control strategies. However, some outer furnace variables are measured, and we can use these measurements to find estimates of unknown inner furnace conditions that in turn can be applied in the furnace control system.

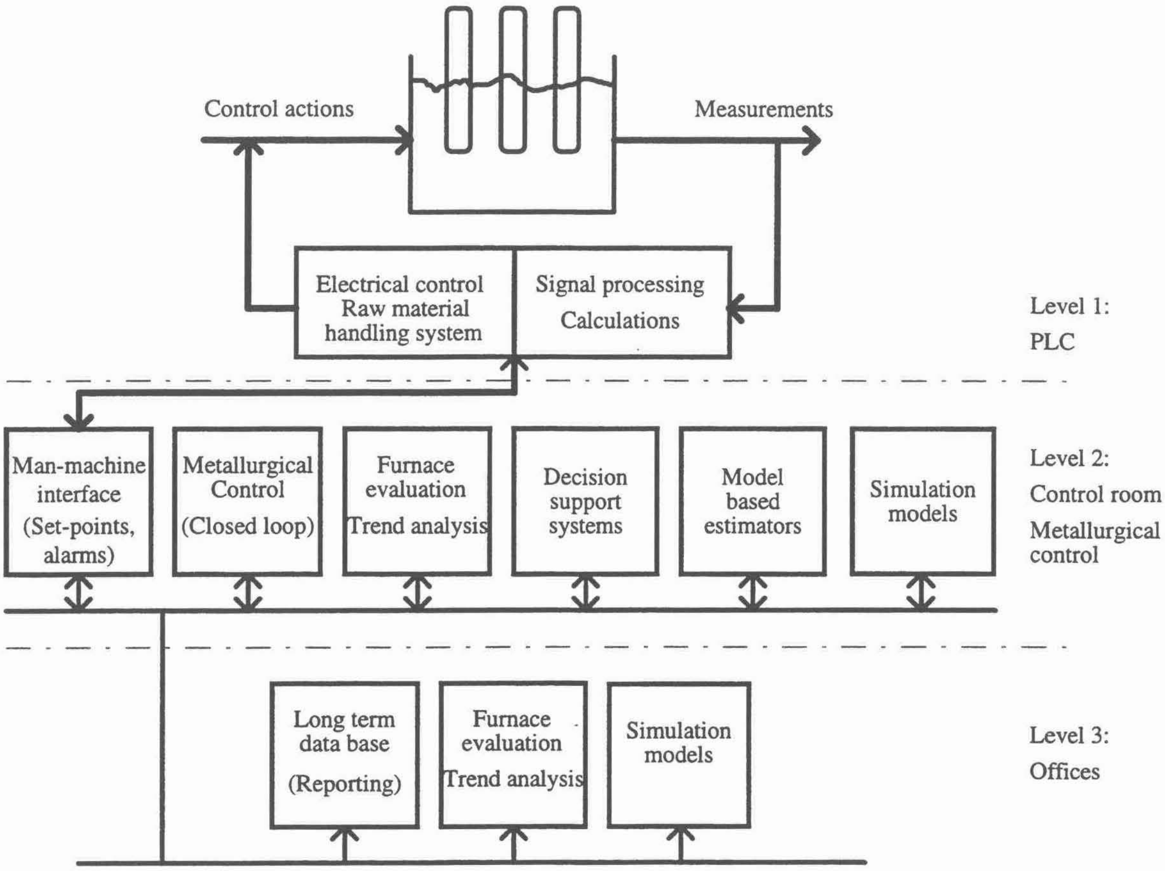

FIG. 1. The new concept for ferrosilicon furnace operation and control.

Model based measurement technique has turned out to be an important tool to increase the information from processes with insufficient measurements. A model based estimator contains a process model that is implemented on-line in parallel to the process, as shown in FIG. 2.

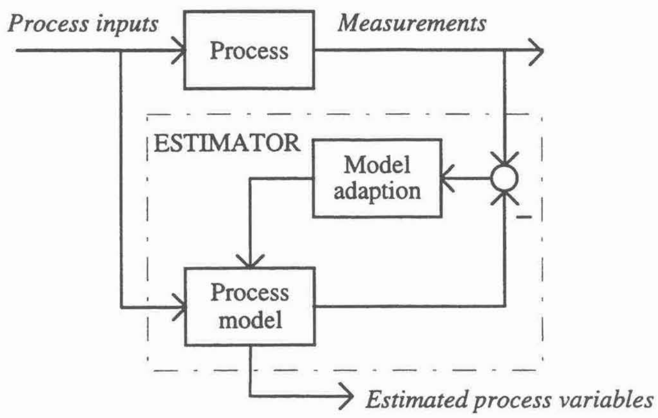

FIG. 2. A model based estimator scheme.

A model adaptation strategy then operates on the deviations between the process measurements and the model outputs. When the model outputs coincide with the process measurements, the model fits the process, and the estimates of the process variables of current interest can be found from the corresponding model variables. The estimated variables can be used as ordinary measurements and applied in control loops as well. The idea of a model based control strategy is to use the estimated variables when controlling the furnace, either directly by an automatic controller or indirectly by an operator.

FeSi furnace estimators

The arcing conditions in a FeSi furnace have previously been investigated in [1]. If we combine dynamic arc models with a transient electrical model of the furnace, we can develop an estimator of the arcing and cavity variables. We have developed such an estimator as part of an electrical simulation model [1], but not yet on-line to the furnace. To develop this estimator into a practical tool at the furnace is a topic for future research.

The stoichiometric model of the (Fe)Si process has regularly been used as a diagnosis tool at several plants for some years [6]. Presently, we are adapting the dynamic simulation model of the Si process and will implement it in the control rooms at the plants, where it can be used to support the furnace evaluation [7, 8]. Moreover, we plan to develop an estimator based on this model to achieve new information about the unknown process conditions in the hearth of the furnace [1, 3].

In the paper we focus on an estimator of the carbon balance in the furnace that has been developed and applied at Elkem Thamshavn furnace #2, producing 75 % FeSi. The estimator uses a time series model of the silica fume production from the furnace [1, 4]. Furthermore, other carbon balance indicators have been derived, based on correlation analysis of furnace variables.

A CARBON BALANCE ESTIMATOR

The carbon balance estimator is based on a time series model of the silica fume flow from the furnace. In the following time series modelling and system identification is briefly outlined [9].

Time series modelling

Assuming a linear system with an input signal $u(t)$ and an output signal $y(t)$ and a constant sampling rate, the input-output relationship of the system can be described by the following general time series model:

$$y(i) = -a_1 y(i-1) - \cdots - a_{ny} y(i-ny) + b_1 u(i-d_u-1) + \cdots + b_{nu} u(i-d_u-nu) + e(i) \tag{1}$$

where $e(t)$ is a white noise signal. This can alternatively be written as:

$$y(i) = -\sum_{k=1}^{ny} a_k y(i-k) + \sum_{k=1}^{nu} b_k u(i-d_u-k) + e(i) \tag{2}$$

The coefficients a and b are the model parameters, i is the unit time variable, $(i\text{-}k)$ denotes the point of time $(i-k\cdot T_S)$ where T_S is the unit time (sampling interval). ny and nu describe the order of the model and show the number of samples in the model of respectively the output and input variables. The time delay τ_u between the process input and output is described by d_u time units, corresponding to $\tau_u = d_u \cdot T_s$.

The model can be identified by a least-square minimization of the error between the measurement $y(t)$ and model output $\hat{y}(t)$. The model can be expressed as:

$$\hat{y}(i) = \varphi(i)^{\mathrm{T}}\Theta \tag{3}$$

by defining a parameter vector Θ and regression vector $\varphi(i)$, containing the set of input and output variables at each point of time:

$$\Theta = \left[a_1, \cdots, a_{ny}, b_1, \cdots, b_{nu}\right]^{\mathrm{T}} \quad \varphi(i)^{\mathrm{T}} = \left[-y(i-1), \cdots, -y(i-ny), u(i-d_u-1), \cdots, u(i-d_u-nu)\right] \tag{4}$$

By defining the following vectors:

$$\mathrm{Y} = \left[y(1), \cdots, y(N)\right]^{\mathrm{T}} \quad \Phi = \left[\varphi(1)^{\mathrm{T}}, \cdots, \varphi(N)^{\mathrm{T}}\right]^{\mathrm{T}} \tag{5}$$

where N is the length of the time series we use to fit the model, the least-square criterion becomes:

$$V(\Theta, N) = \tfrac{1}{2}\sum_{i=1}^{N}\left(y(i) - \varphi(i)^{\mathrm{T}}\Theta\right)^2 = \tfrac{1}{2}(\mathrm{Y} - \Phi\Theta)^{\mathrm{T}}(\mathrm{Y} - \Phi\Theta) \tag{6}$$

and a least-square solution of the parameter vector Θ can be found as:

$$\hat{\Theta} = \left[\Phi^{\mathrm{T}}\Phi\right]^{-1}\Phi^{\mathrm{T}}\mathrm{Y} \tag{7}$$

Similarly, a *recursive* least square estimate of the parameters can be derived as:

$$\begin{gathered} \Theta(i) = \Theta(i-1) + \mathrm{P}(i)\varphi(i)\left(y(i) - \varphi^{\mathrm{T}}(i)\Theta(i-1)\right) \\ \mathrm{P}(i) = \frac{1}{\lambda}\left[\mathrm{P}(i-1) - \mathrm{P}(i-1)\varphi(i)\left(\varphi(i)^{\mathrm{T}}\mathrm{P}(i-1)\varphi(i) + \lambda\right)^{-1}\varphi(i)^{\mathrm{T}}\mathrm{P}(i-1)\right] \end{gathered} \tag{8}$$

where we have introduced a *forgetting factor* λ in the least square criterion $(0 < \lambda < 1)$:

$$V(\Theta, N) = \tfrac{1}{2}\sum_{i=1}^{N}\lambda^{N-i}\left(y(i) - \varphi(i)^{\mathrm{T}}\Theta\right)^2 \tag{9}$$

This means that data that is n unit times old will be weighed by λ^n, and that the estimator will have a "memory horizon" of $T_s/1-\lambda$.

<u>The silica fume flow model</u>

The carbon balance estimator contains a time series model of the silica fume flow from the furnace. It is assumed that the silica fume flow $y_{\mathrm{SiO}}(i)$ can be expressed in terms of the fixed-carbon content of the added charge $u_{\mathrm{FixC}}(i)$, the mean electrode holder position $u_{\mathrm{HP}}(i)$, and the mean harmonics content in the hearth voltages $u_{\mathrm{OH}}(i)$:

$$\begin{aligned} \hat{y}_{\mathrm{SiO}}(i) = & -\sum_{k=1}^{nSiO} a_k y_{\mathrm{SiO}}(i-k) + \sum_{k=1}^{nFixC} b_{\mathrm{FixC},\,k} u_{\mathrm{FixC}}(i - d_{\mathrm{FixC}} - k) \\ & + \sum_{k=1}^{nHP} b_{\mathrm{HP},\,k} u_{\mathrm{HP}}(i - d_{\mathrm{HP}} - k) + \sum_{k=1}^{nOH} b_{\mathrm{OH},\,k} u_{\mathrm{OH}}(i - d_{\mathrm{OH}} - k) \end{aligned} \tag{10}$$

The model properties are characterized by the choices of the model orders *nSio*, *nFixC*, *nHP* and *nOH*, the time delays d_{FixC}, d_{HP} and d_{OH}, the forgetting factor λ, and the sampling time T_S.

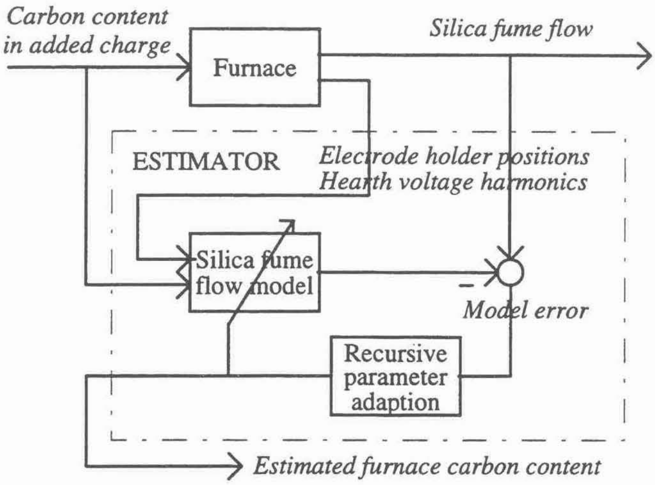

FIG. 3. The carbon balance estimator scheme.

In addition, a proper filtering of the variables entering the estimator, is vital. The model in Eq. 10 is implemented in a recursive parameter estimator scheme, as illustrated in FIG. 3. The coefficient of the fixed-carbon input $b_{\mathrm{FixC},\,1}$ in the model indicates the carbon balance of the furnace and can tell whether the furnace is overcoked or undercoked. FIG. 4 shows the principle relationship between the furnace's carbon balance and the silica fume flow [6].

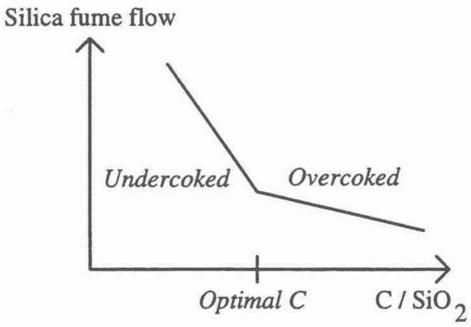

FIG. 4. The principal relationship between silica fume flow and the furnace's carbon balance.

The curve slope of the silica fume flow is fundamentally different in undercoked and overcoked conditions. The estimated model parameter $b_{\mathrm{FixC},\,1}$ will be analogous to the curve slope in FIG. 4, provided that the model structure in Eq. 10 describes the silica fume flow satisfactorily. Hence, the estimated model parameter indicates the furnace's carbon balance. If the estimated parameter $b_{\mathrm{FixC},\,1}$ is below some negative limit β, the furnace is undercoked. Likewise, if $b_{\mathrm{FixC},\,1}$ is between β and 0, the furnace is overcoked. If $b_{\mathrm{FixC},\,1}$ is positive, other furnace conditions predominate the fixed-carbon variation in the added raw materials and we have a "slagging" furnace.

Implementation

The first version of the carbon balance estimator was implemented at Elkem Thamshavn furnace #2 in 1992. This version of the model had a simple structure using one term of the added fixed-carbon content $u_{\mathrm{FixC}}(i)$ and two terms of the holder position $u_{\mathrm{HP}}(i)$:

$$\hat{y}_{\mathrm{SiO}}(i) = b_{\mathrm{FixC},\,1} u_{\mathrm{FixC}}\left(i - d_{\mathrm{FixC}} - 1\right) + b_{\mathrm{HP},\,1} u_{\mathrm{HP}}\left(i - d_{\mathrm{HP},\,1} - 1\right) + b_{\mathrm{HP},\,2} u_{\mathrm{HP}}\left(i - d_{\mathrm{HP},\,2} - 1\right) \qquad (11)$$

The experience with the estimator was to some extent positive. It gave reasonable estimates of the carbon balance for some months and was regularly used in the furnace evaluation. However, after some time the estimates became uncertain, and the estimator drifted off as result of changing furnace operation and raw materials. This is a general draw-back with black-box models: The model is fitted towards process data from a specific period, and if the process changes, the model becomes incorrect and likewise any estimator based on it. Therefore, such estimators should be implemented in a way that provides easy modifications of the model structure by adapting model orders, time delays, filtering and forgetting factor. Unfortunately, this was not the case with the first version of the estimator, and it was difficult to adapt the model to changes in the furnace operation.

In 1994 a new metallurgical control computer system was installed at Elkem Thamshavn furnace #2 (FIX DMACS 5.0 Windows), covering data collection, trend presentation and metallurgical control. This system gave new possibilities regarding implementation of estimators due to improved data communication (DDE) and user interface. Thus, it was decided to develop a new version of the estimator, securing a simple modification of the model structure. Now, the general model structure in Eq. 10 is implemented, and any structure can be applied. The present version of the model contains one term of the added fixed-carbon content $u_{\mathrm{FixC}}(i)$ and one term of the hearth voltage harmonics $u_{\mathrm{OH}}(i)$:

$$\hat{y}_{\mathrm{SiO}}(i) = b_{\mathrm{FixC},\,1} u_{\mathrm{FixC}}(i - d_{\mathrm{FixC}} - 1) + b_{\mathrm{OH},\,1} u_{\mathrm{OH}}(i - d_{\mathrm{OH}} - 1) \tag{12}$$

The sampling time is $T_S = 30$ minutes, and all variables are lowpass filtered over 12 hours. The time delays are chosen as $d_{\mathrm{FixC}} = 10$ hours and $d_{\mathrm{OH}} = 4$ hours, and the applied forgetting factor is $\lambda = 0.99$. The estimated model parameter indicates the furnace's carbon balance as follows:

$$b_{\mathrm{FixC},\,1}(t) \begin{cases} < -1.0 & \text{Furnace undercoked} \\ -1.0 < (\cdot) < 0 & \text{Furnace overcoked} \\ > 0 & \text{"Slagging" (other effects predominate)} \end{cases} \tag{13}$$

OTHER CARBON BALANCE INDICATORS

The relations between the carbon balance and other furnace variables can be used to develop further indicators of the furnace condition. FIG. 5 shows the principle relationship between the furnace's carbon content and three performance indexes, the specific energy consumption, the silicon recovery and the metal production rate. The figure shows that the correlation between the furnace's carbon balance and a performance index at an undercoked condition is opposite to the correlation at an overcoked condition. On this basis simple carbon balance indicators have been derived, based on correlation calculations between the fixed-carbon content in the added charge and the three performance variables, the specific energy consumption, the silicon recovery and the metal production.

1. Use daily values of the variables, averaged over four days to reject any occasional variations.

2. Look at a moving horizon of the 12 last days of the averaged variables and calculate the correlation coefficients between the added fixed-carbon content and the three performance variables as described below.

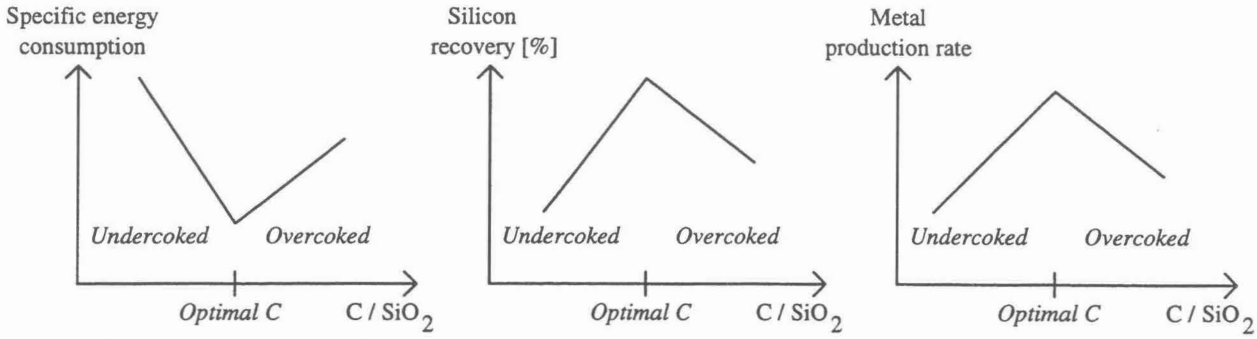

FIG. 5. Principle relationships between the carbon balance and the furnace performance indexes.

Given two time series x(k) and y(k) of N samples with mean values $\bar{x}$ and $\bar{y}$ and standard deviations σ_x and σ_y, the correlation coefficient C_{xy} can be calculated by:

$$C_{xy} = \frac{1}{N}\sum_{k=1}^{N}(x(k)-\bar{x})\cdot(y(k)-\bar{y}) \Big/ \sigma_x \cdot \sigma_y \tag{14}$$

The correlation coefficient varies between -1 and 1. Positive values correspond to positive co-variation and negative values to the opposite. If $C_{xy} = 0$ the two series are uncorrelated.

3. The calculated correlation coefficients indicate the furnace's carbon balance. If a coefficient is negative, the respective curve in FIG. 5 has a downward trend. Similarly, when the coefficient is positive, we have an upward trend. Since the trend directions depend on the carbon balance, we can determine the carbon balance from the calculated correlation coefficients. To obtain a more robust indicator, we have introduced a dead-band of ± 0.25 around zero and compare the coefficients to the dead-band limits instead of zero:

$$\text{Undercoked} = \begin{cases} C_{\text{FixC-SEC}} < -0.25 \\ C_{\text{FixC-Metal}} > +0.25 \\ C_{\text{FixC-Si\_rec}} > +0.25 \end{cases} \quad \text{Overcoked} = \begin{cases} C_{\text{FixC-SEC}} > +0.25 \\ C_{\text{FixC-Metal}} < -0.25 \\ C_{\text{FixC-Si\_rec}} < -0.25 \end{cases} \tag{15}$$

The estimates of the carbon balance from this method will be some days *delayed* compared to the estimator based on the silica fume flow model.

RESULTS

FIG. 6 shows the result of the carbon balance estimator in Eq. 12 implemented at Elkem Thamshavn furnace #2. If we apply the rules in Eq. 13 on the estimated parameter $b_{\text{FixC},1}$, we find that the furnace was *undercoked* in the periods (44-52, 55, 59-62, 94-97, 99-103), *overcoked* in the periods (40-43, 53-54, 56-58, 63-64, 86-93, 98, 104-115), and that slagging conditions were dominating in the period (65-85).

FIG. 7 shows the results of the three correlation indicators as described above with furnace data from the same period. By applying the rules in Eq. 15 on the calculated correlation coefficients by demanding three similar indications, we find that the furnace was *undercoked* in the periods (45-49, 59-61, 74-78, 101-104) and *overcoked* in the periods (36-41, 83-96).

The estimators give comparative indications of the carbon balance. A major drawback with the estimators is that they are using the assumed fixed carbon content in the added charge.

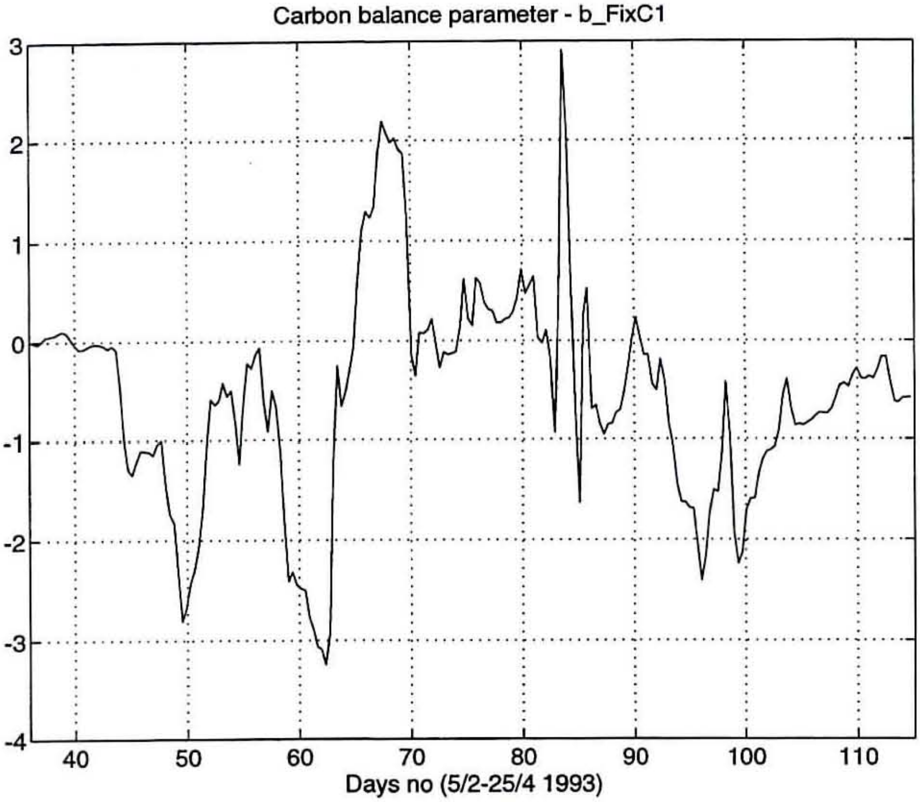

FIG. 6. The estimated carbon balance parameter.

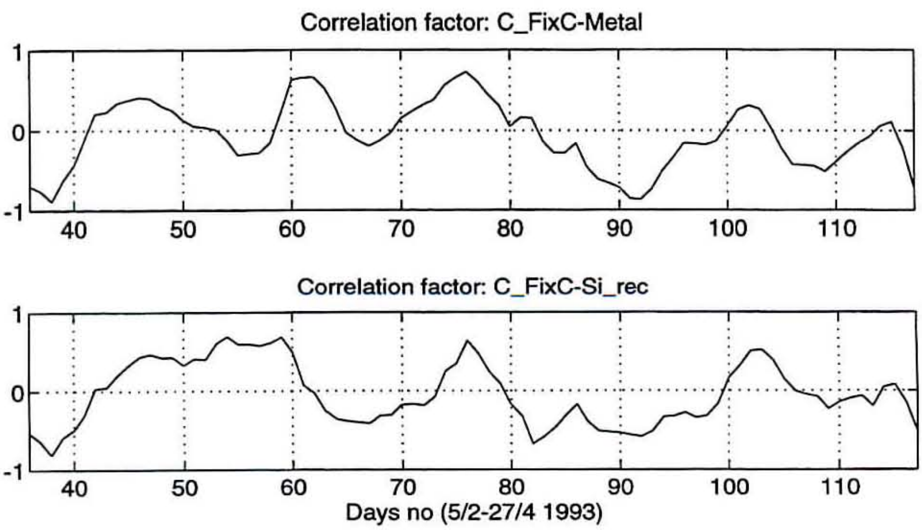

FIG. 7. The carbon balance correlation coefficients.

Consequently, unknown fixed carbon variation will result in incorrect estimates. Moreover, the reactivity of different carbon materials used in the charge mix will effect the performance of the estimators, because the estimators are using the fixed carbon level and not the charge reactivity. Thus, changes in the charge reactivity will not be seen as long as the fixed carbon content is kept constant, leading to incorrect estimates. This is a subject for improvements in near future.

CONCLUSIONS

To achieve steady FeSi furnace operation the information from the furnace hearth have to be increased. In this process application of model based estimators will be an important part. We have developed a carbon balance estimator using a time series model of the silica fume flow and further indicators based on correlation analyzis. The estimators are implemented at Elkem Thamshavn furnace # 2, where they are regularly used as diagnosis tools in the furnace operation. Further development of model based estimators for FeSi furnaces is a topic for continuous work.

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