MATHEMATICAL MODELING OF THE BOF FOR ENDPOINT PREDICTION USING EFSOP® TECHNOLOGY[1]

Omar Davis [2]
Vittorio Scipolo [2]
Armando Vazquez [3]

Abstract

Accurate endpoint prediction is a critical control tool in the operation of a BOF. It provides the steelmaker with increased yield & productivity while reducing operating costs. Traditionally, operators have relied on static charge models for endpoint prediction of temperature & carbon. These models have a limited ability to predict endpoint because they do not account for process dynamics and are adversely affected by uncertainties in the initial conditions. The EFSOP® strategy uses, a rigorous, non-linear dynamic model to predict the mass, temperature & compositions of the hot metal, slag and gas phases with closed-loop control and continuous tuning from the feedback of real-time off-gas composition measurements. To enhance endpoint prediction with a Sublance System in place, a supplemental regression model was incorporated. This model, using either an inblow measurement from the Sublance or the predictions of Carbon and temperature from the dynamic model, calculates the endpoints of Carbon and temperature in the final stages of the blow.

The EFSOP® strategy for end-point detection uses real-time off-gas analysis, along with measured process variables, to determine more accurately when the temperature & carbon end-points have been reached & signal the end of the heat. Online results for temperature and carbon were within 12º C and 1.5 points of carbon, standard deviations, respectively (when compared with actual Sublance measurements). This accuracy provided the steelmaker with the opportunity to employ direct tapping of the heat, thereby reducing tap-to tap time and the cost of operation and maintenance of the Sublance System.

Keywords: Off-gas analysis; BOF steelmaking; Dynamic model; End-point detection; Mass balance; Energy balance; Sublance

MODELAMENTO MATEMÁTICO DO BOF PARA A PREVISÃO DO PONTO FINAL USANDO A TECNOLOGIA EFSOP®

Resumo

A previsão precisa do ponto final é uma ferramenta de controle crítica na operação de um BOF. Ela propicia ao aciarista um aumento do rendimento e produtividade e uma redução dos custos operacionais. Tradicionalmente os operadores confiam em modelos de carga estáticos para a previsão do ponto final de temperatura e carbono. Esses modelos possuem uma capacidade limitada de previsão do ponto final pois eles não consideram a dinâmica do processo e são desfavoravelmente afetados por incertezas nas condições iniciais. Com a estratégia EFSOP®, um modelo estado-estado dinâmico foi utilizado para prever a massa, a temperatura e as composições do gusa líquido, fases escória/gás com controle em circuito fechado e ajuste contínuo pelo retorno de medições da composição dos gases de exaustão em tempo real. Para melhorar a previsão do ponto final com um Sistema de Sublança instalado, foi incorporado um modelo suplementar. Este modelo, usando uma medição no sopro da Sublança ou as previsões de carbono e temperatura do modelo dinâmico, calcula os pontos finais de carbono e temperatura nas fases finais do sopro. A estratégia EFSOP® para a deteção do ponto final utiliza a análise em tempo real dos gases de exaustão, junto com variáveis de processo medidas, para determinar mais precisamente quando os pontos finais de temperatura e carbono foram atingidos e sinalizar o final da corrida. Resultados online para temperatura e carbono estiveram entre 12ºC e 1,5 pontos, desvios padrão, respectivamente (quando comparados com medições reais da Sublança). Essa precisão permitiu que os aciaristas empregassem vazamento direto da corrida, reduzindo desta forma o tempo de tap-to-tap e os custos de operação e manutenção do Sistema de Sublança.

Palavras-chave: Análise de gases de exaustão; Aciaria BOF; Processos de combustão; Eficiência energética.

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[1] *Technical contribution to the 41st Steelmaking Seminar – International, May, 23h-26th 2010, Resende, RJ, Brazil.*

[2] *Technology & Development, Tenova Goodfellow Inc.*

[3] *Sales & Marketing, Tenova Goodfellow Inc.*

EFSOP® Technology for the BOF

Tenova, comprised of a network of 30 operative companies located on five continents, is committed to the development of technology in the areas that greatly impact the future of the industries it serves. Energy efficiency, reduced operating costs, increased productivity, improving the environment and higher quality products are the drivers for Tenova innovation in the steel industry.

Tenova Goodfellow's EFSOP® (Expert Furnace System Optimization Process) is a dynamic process control and optimization system that is based on the real-time measurement of off-gas composition. Though originally developed for steelmaking in the electric arc furnace (EAF), the technology has been applied to oxygen steelmaking for endpoint control. The EFSOP® system for the basic oxygen furnace (BOF) was installed on a 345-ton vessel, used to convert a nominal mix of 270 tons of hot metal and 75 tons of scrap to steel.

Figure 1 is a schematic of the EFSOP® system, as applied to the BOF. The system is comprised of:

- A patented water-cooled off-gas sampling probe, designed to withstand the steelmaking environment.
- The EFSOP® off-gas analyzer, for sample conditioning and analysis equipped with a customized purging system to keep the probe clear of dust and to eliminate plugging.
- Passive infrared gas sensor for off-gas temperature measurements.
- A supervisory control and data acquisition (SCADA) system.

The sampling probe is installed through a port in the panels of the BOF fume system. The probe is located downstream of the combustion gap to ensure that the sampled off-gases are completely mixed and combusted. The gases are drawn through a heated line to the EFSOP® analyzer, where they are analyzed, in real-time, for oxygen, carbon dioxide, carbon monoxide and hydrogen. An infrared pyrometer was used to measure the temperature of the off-gas at the sampling location. This installation of the EFSOP® analysis system for the BOF has proven to be highly reliable; with over 99% analysis uptime during the oxygen blow. To ensure a valid off-gas sample throughout the blowing period, the system is purged during natural breaks in the process (e.g. during tapping and between heats). This is sufficient to prevent plugging of sampling probe.

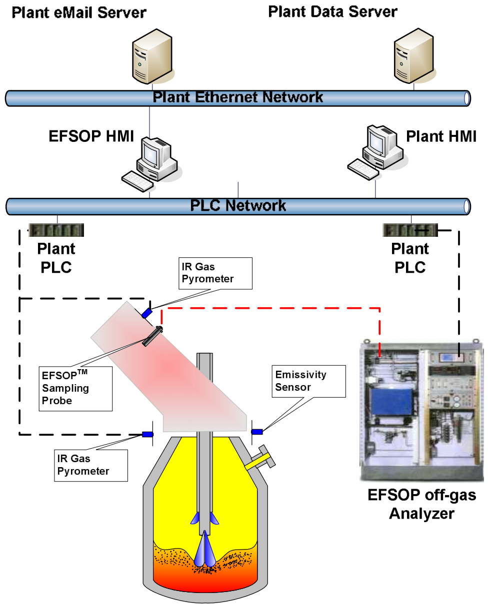

Figure 1. Schematic of the EFSOP® system applied to the BOF

Composition measurements, as well as operational alarms and outputs from the analyzer are linked to the plant's PLC network. The EFSOP® SCADA (Supervisory Control and Data Acquisition) computer is linked to the same network and reads and logs off-gas data, as well as all relevant process data at a frequency of one second. Historical and real-time trends of the data are made available to the operator. Off-gas data, process data, and EFSOP® system alarms are emailed to Tenova Goodfellow's office in Mississauga, Canada, allowing process engineers to follow the operation remotely.

A plot of the measured off-gas composition profile for a representative heat is presented in Figure 2. The pattern displayed in the plot is typical and fairly consistent from one heat to the next. This particular plant operates with a suppressed combustion system incorporating a sublance; hence the reduction in the measured values of carbon monoxide and carbon dioxide when the blow is temporarily stopped (inblow) for the measurements of carbon and temperature. The variation in the off-gas composition during the heat is typical for this shop, and is the result of flux additions and process variations, such as changes in lance height, over the course of the blow. The relatively high ratio of carbon monoxide over carbon dioxide is indicative of a suppressed combustion system, where oxidation is limited. After oxygen ignition at the start of the blow, the carbon monoxide ramps upwards as the lance is lowered and decarburization begins. The slight delay is attributed to the early oxidation of the elements with a greater affinity for oxygen than carbon, (e.g. silicon and manganese). Towards the end of the heat carbon monoxide falls rapidly as carbon in the bath is depleted.

It is well accepted that the kinetics of decarburization are driven by the rate of mass transfer of dissolved carbon to the reaction interface between liquid metal and iron oxide. At high carbon concentrations (approximately greater than 0.3% carbon), the mass transfer rate is sufficiently high that the rate of decarburization is controlled by the rate of oxygen supply to the steel bath. Below this concentration, the rate of decarburization is limited by the rate of carbon diffusion to the reaction interface.(1) This mechanism is evident in the off-gas profile where carbon dioxide concentrations tend to remain fairly constant throughout the heat and to then decrease sharply as carbon is depleted near the end of the blow.

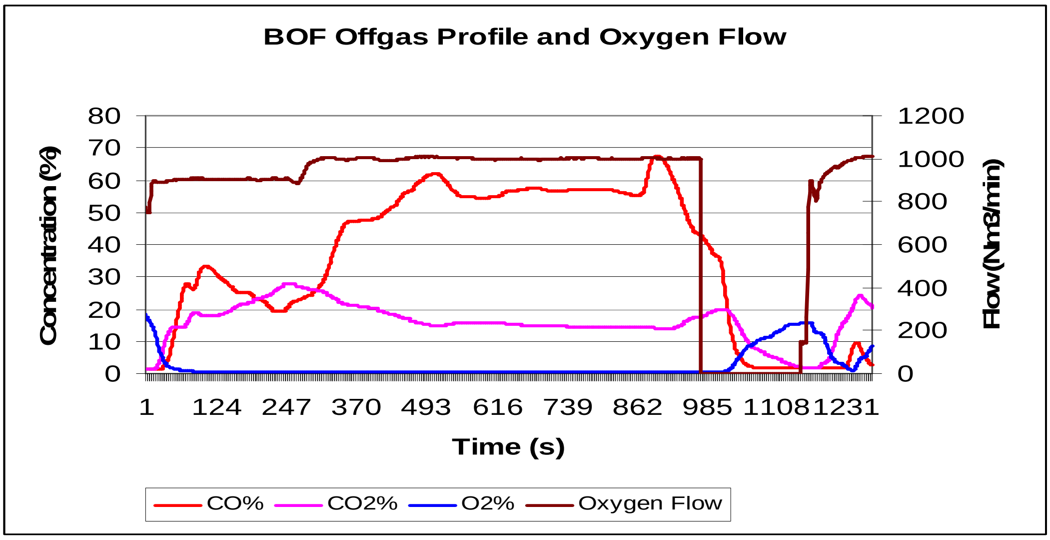

Figure 2. Measured downstream off-gas composition

Objectives of the Models

The main objective of the models is to provide an accurate indication, in real-time, of when target temperature and carbon have been achieved. Such an indication would reduce or eliminate the need for reblows and reduce the reliance on often expensive and maintenance intensive measuring devices. This will ultimately increase yield and productivity while reducing overall operating costs. In addition to endpoint temperature and carbon, real-time slag composition is also generated. This can be used for tighter control of flux additions, thereby reducing refractory wear in the furnace. Standard operating procedures for this shop led to the development of two models; an inblow model which tells the operator when to take the inblow measurement and an endpoint model which indicates when target conditions have been attained. The inblow model executes from the start of blow to the end of blow, while the endpoint model executes on resumption of oxygen after the inblow measurement has been taken (see Figure 3). Validation is achieved by comparison of actual sublance measurements with the predictions from the models. The descriptions of both models are provided below.

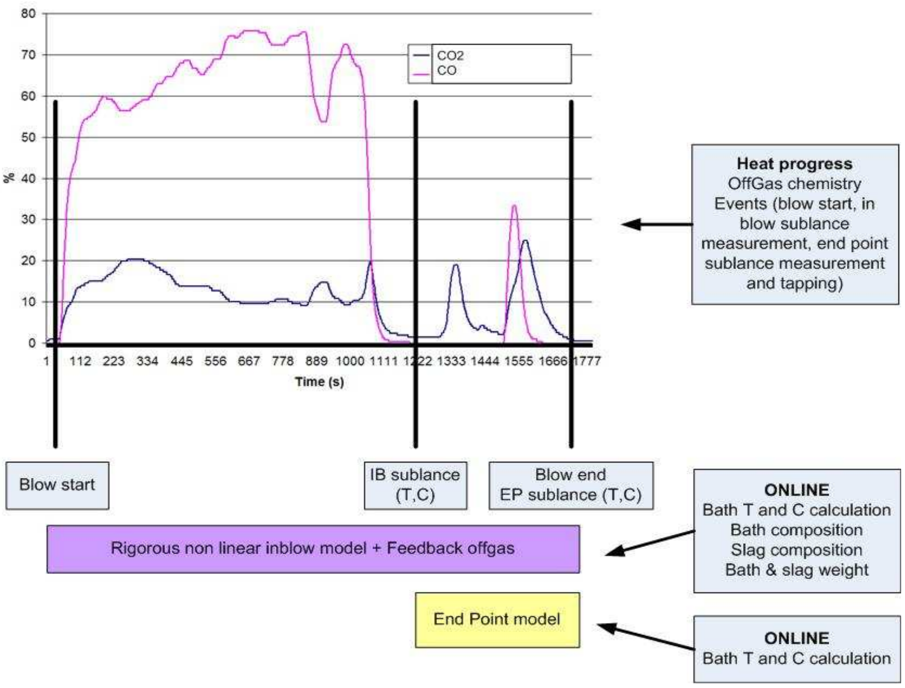

Figure 3. Execution sequence of inblow and endpoint models

Rigorous Non-linear Dynamic Model (Inblow Model)

First principles of mass and energy balances, thermodynamics and reaction kinetics were applied to develop the equations that predict the rates of change of the various processes occurring inside the furnace. The processes modeled were:

- Metallic scrap melting
- Addition and melting of fluxes and coolants
- Oxidation of iron, carbon, silicon, manganese and phosphorous
- Change in steel weight, temperature and composition.

Using process operating data on charged and added materials from the plant PLC network, the online model calculates in real-time the temperature, mass and composition of the steel bath, slag and gas phases. With its input structure, the model accounts for the different composition of multiple scrap charges and flux additions. An adaptive technique was employed whereby offgas measurements were used in feedback mode to continuously update and tune the model with an error minimization algorithm.

The results obtained are presented in Figures 4 to 8 below. In Figure.4, the metallic scrap melting model determines the rate of liquid steel mass rate to the hot metal as indicated by the resultant increase in the mass of the bath. Towards the end of the blow, the slight decrease in the mass of hot metal is due to increased oxidation of iron that occurs as the carbon in the bath is depleted. Figure 5 shows the profile of the melting of solid fluxes to produce molten slag. A plot of the hot metal and scrap temperature profile (see Figure 6) shows a decrease in temperature of the hot metal and a corresponding increase in the temperature of the metallic scrap and fluxes accounting for the energy required for heating and melting at the point of addition. The profile of predicted bath carbon is shown in Figure 7. As expected, the mass of carbon increases early in the heat resulting from the preferential oxidation of silicon over carbon in the initial stages of the heat while melting scrap provides additional carbon in the hot metal. This is followed by a period of steady oxidation where the rate of decarburization is driven by the rate of oxygen supplied. No decarburization takes place when the blow is temporarily stopped for the inblow measurement, after which oxidation resumes at a lower rate due to depleted carbon. A profile of slag-phase silicon dioxide and iron oxide (see Figure 8) shows a rapid increase in the generation of silicon dioxide early in the heat and a fairly constant mass of iron oxide over the course of the blow. In fact, the rate of iron oxidation remains relatively low throughout the heat, until the critical point is reached. At that point, most of the supplied oxygen will oxidize iron as carbon is depleted.

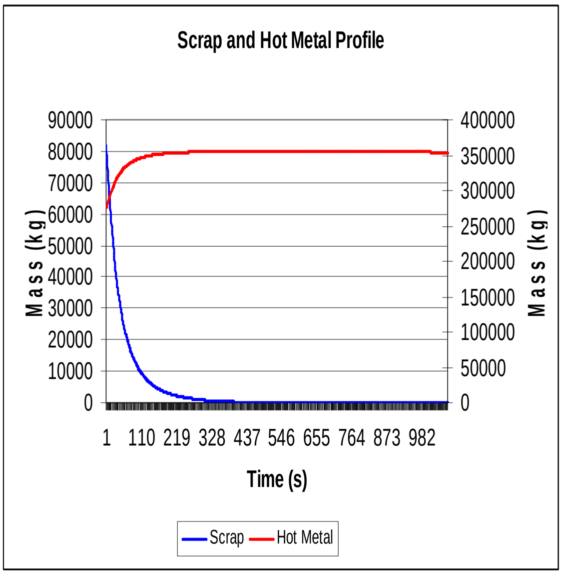

Figure 4. Model output scrap & hot metal profile

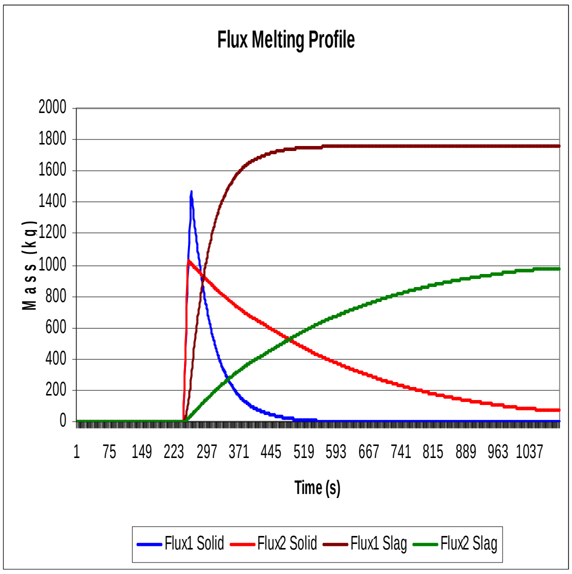

Figure 5. Flux melting profile

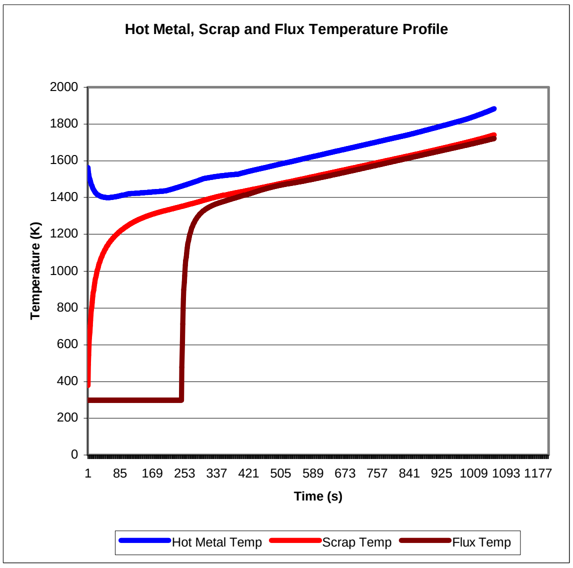

Figure 6. Temperature profile for hot metal, Scrap & flux

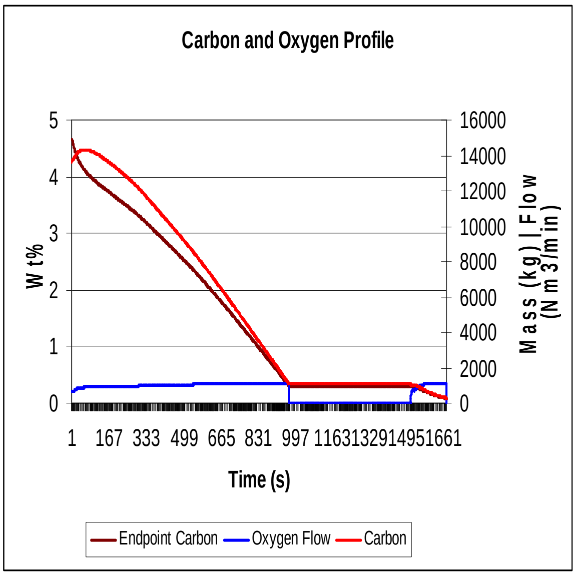

Figure 7. Carbon and lance oxygen profile.

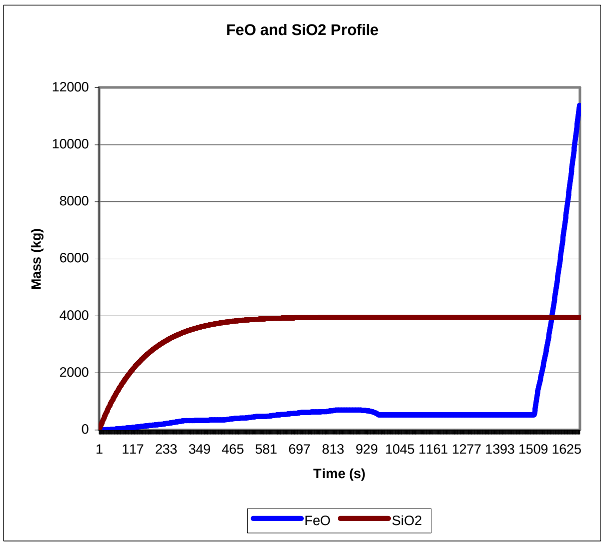

Figure 8. Iron oxide and silicon dioxide profile

Regression Model (Endpoint Model)

While the inblow model is fully capable of predicting throughout the high and low carbon regimes, it was determined that additional accuracy could be achieved by using the inblow measurement of temperature and carbon from the sublance as a reasonably good initialization point for a subsequent model. Using basic equations, the rate of decarburization and the subsequent temperature increase as a result of oxygen consumption were determined. Tuning parameters were obtained by regression analysis of actual operational data and the use of real-time off-gas measurements, and the temperature reducing effect of the fluxes added after inblow was studied and also included. Validation results of this model (along with the inblow model) are provided in the section below.

Model Performance and Evaluation

The results obtained for the performances of the dynamic and the regression model are presented in Tables 1 and 2, respectively.

In Table 1, the temperature and carbon end-point prediction provided by the dynamic model is compared to the in-blow measurement taken with the sublance. The comparison was made for 148 heats and shows reasonable agreement between the model and the measurement. The standard error between the predicted and measured temperature was found to be only 24^{o} C while that of in-blow carbon was 0.254 wt%.

Table 1: Performance results for dynamic model (Inblow Evaluation)

	Average Sublance Measurement	**Average Model Prediction**	**Standard Error**	**Number of Heats**
Temperature (^{0}C)	1635.33	1629.51	23.81	148
Carbon (wt %)	0.270	0.290	0.254	148

The end-point prediction using the regression model is compared against the actual end-point measured at the end of the blow. The results for the 155 heats evaluated are presented in Table 2. As indicated, the standard error for temperature was found to be 11.9° C while that for carbon was 0.014 wt%.

Table 2: Performance results for regression model (Endpoint Evaluation)

	Average Sublance Measurement	**Average Model Prediction**	**Standard Error**	**Number of Heats**
Temperature (⁰C)	1677.9	1674.3	11.9	155
Carbon (wt %)	0.0467	0.0495	0.014	155

Conclusions and Future Work

Online evaluation of the EFSOP® approach to endpoint prediction indicated that both carbon and temperature were predicted with reasonably good accuracy. The inblow model was able to predict within 24º C of standard error for temperature and 0.25 wt% for carbon. This level of accuracy made it possible, during the evaluation period, to signal the operator as to when to take an inblow measurement. Historically, at this particular plant, the inblow sample was taken according to a static charge model. As this model does not take into account the dynamics of the process, this method has historically resulted in the sample being taken too early or too late from ideal; negatively affecting both process logistics and the ability of the static model to indicate end-of-blow. It is envisioned that eventually the model will replace the inblow sublance sample. Similarly, the favorable results provided by the end-point model suggest that the sub-lance use at the end of the blow could be reduced significantly. Furthermore, the accuracy in end-point prediction provided by the EFSOP® system will enable the operator to target end-blow according to desired grade, greatly reducing yield losses and improving process logistics.

To this end, the goal of future trials will be to demonstrate the model's utility for end-point prediction without inblow sublance measurement. Not only would the ability to blow and tap, without stopping to take an inblow measurement, decrease the maintenance costs associated with the sublance system, but would also provide an increase in both yield and productivity given the expected reduction in tap-to-tap time and the reduction in the number of reblows.

REFERENCES

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