APPLICATION OF EFSOP ® TECHNOLOGY TO BOF STEELMAKING[1]

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Abstract

Tenova Goodfellow Inc. (TGI), a word-leader in the use of off-gas monitoring and analysis for optimization of EAF steelmaking furnaces, has expanded the application of their Expert Furnace System Optimization Process (EFSOP®) to BOF steelmaking. End-point detection, based on off-gas analysis, is the key goal for this process. A reliable method of determining temperature and carbon end-point provides the benefits associated with minimizing the number of turn-downs and reblows and subsequently provide the steelmaker with: increased yield; increased productivity through a reduction in heat time; and a reduction in green-house gas emissions. A second phase of the project will focus on the use of EFSOP®, in combination with a slag-splashing refractory management system, a modified dual-flow lance design and an advanced slop detection system to maximize recovery of chemical energy through post-combustion. This paper reports on TGI's progress to date and shows preliminary results of off-gas based BOF modeling efforts and their use for end-point prediction.

Key words: Off-gas analysis; BOF steelmaking; Environmental; End-point detection.

APLICAÇÃO DA TECNOLOGIA EFSOP ® EM ACIARIAS BOF

Resumo

Tenova Goodfellow Inc. (TGI), uma líder mundial no uso do monitoramento e análise de gases de exaustão para otimização de Fornos Elétricos a Arco em siderúrgicas, expandiu a aplicação de seu *Expert Furnace System Optimization Process* (EFSOP®) para os convertedores BOF. Detecção do ponto final (*end point*), baseada na análise dos gases de exaustão, é o objetivo chave para este processo. Um método confiável de determinação do ponto final de temperatura e carbono resulta em benefícios associados com a minimização do número de *turn-downs* e ressopros e, subseqüentemente, garante ao aciarista: maior rendimento; maior produtividade através da redução do tempo de aquecimento; e a redução de emissões de gases de efeito estufa. Uma segunda fase do projeto focará o uso do EFSOP® combinado com um sistema *slag-splashing* de gerenciamento de refratário, um projeto de lança de fluxo duplo modificado e um sistema avançado de detecção de *slop* para maximizar a recuperação de energia química através da pós-combustão. Este trabalho relata o progresso da TGI até a data e mostra resultados preliminares de esforços de modelamento de BOF baseado em gases de exaustão e sua aplicação na previsão do ponto final.

Palavras-chave: Análise de gases de exaustão; Aciaria BOF; Meio ambiente; Detecção do ponto final.

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2 *Tenova Goodfellow*

1 Introduction

The Goodfellow Expert Furnace System Optimization Process (EFSOP®) is a dynamic control and optimization system, originally developed for the electric arc furnace (EAF) that is based on the real-time measurement of off-gas composition and process data.[1-9] Through funding provided in part by Sustainable Development Technology Canada (SDTC), EFSOP® is being applied to BOF steelmaking, Cement and Thermal Power industries. SDTC is a not-for-profit Canadian foundation created to foster the development and transfer of leading technologies to improve energy efficiency and reduction green-house gas emissions.

The first EFSOP® system for BOF's has been installed on a 165 ton BOF vessel that uses 45 tons of scrap to supplement 120 tons of hot metal. Initially, end-point detection, based on off-gas analysis, is the key goal for the installation there. A reliable method of determining temperature and carbon end-point provides the benefits associated with minimizing the number of turn-downs and re-blows and subsequently provide the steelmaker with: increased yield; increased productivity through a reduction in heat time; and a reduction in green-house gas emissions. Future efforts will focus on providing optimal control of oxygen rate and lance height over the course of the heat; in response to process measurements, off-gas composition, temperature measurements and modelled process parameters (bath and slag composition). In this second phase of the project EFSOP® will be used, in combination with a slag-splashing refractory management system, a modified dual-flow lance design and an advanced slop detection system to maximize recovery of chemical energy through post-combustion.

A schematic of the EFSOP® system applied to the BOF is shown in
Figure 1 and includes the following components:

- A water-cooled off-gas sampling probe
- The EFSOP® gas-analysis system
- Supervisory Control and Data Acquisition (SCADA) system
- Passive infrared gas pyrometer for off-gas temperature measurement.

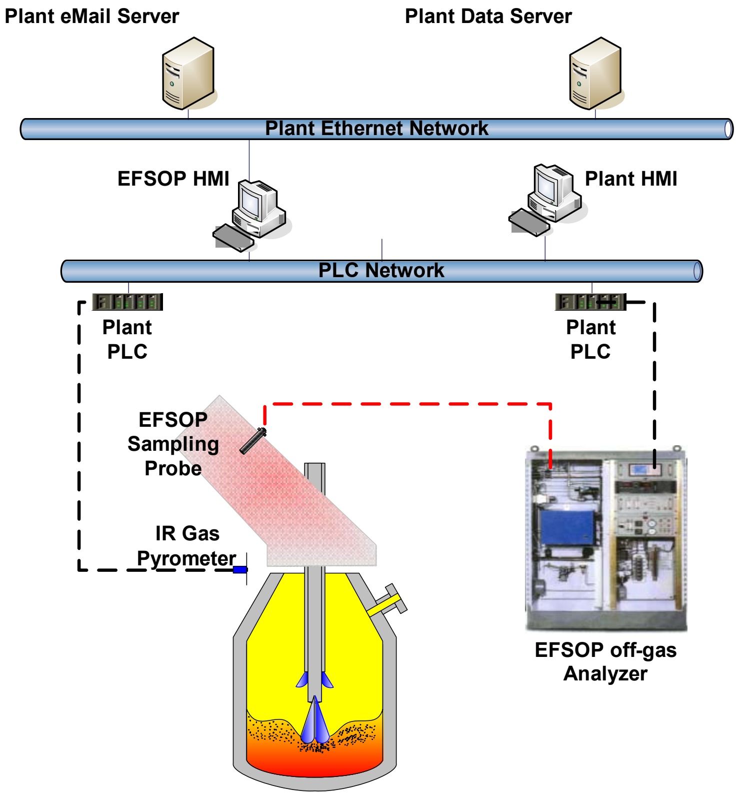

Figure 1. Schematic of the EFSOP® System applied to the BOF

A patented, water-cooled sampling probe, designed to withstand the harsh steelmaking environment, is installed through a port in panels of the BOF fume system. The probe is located sufficiently downstream of the combustion gap to ensure that the sampled gases are completely mixed and combusted. The extracted gases are drawn through a heated sampling line to the EFSOP® gas analysis and conditioning system where they are analyzed for oxygen (O_2), carbon dioxide (CO_2), carbon monoxide (CO), and hydrogen (H_2). Two infrared pyrometers, one located at the combustion gap and a second one at the downstream sampling location, are used to measure the temperature of the off-gas. The EFSOP® analyzer was installed and commissioned in late 2006 and has been operating and collecting process data with over 95% reliability.

In addition to sampling and analysis, the EFSOP® analyzer performs a secondary function of controlling the back-purging of the sampling circuit. To ensure a valid off-gas sample throughout the blowing period, the system is only purged during natural breaks in the process (e.g. during charging and tapping). Composition measurements, as well as operational alarms and outputs from the analyzer are linked to the plant's PLC network. The EFSOP® SCADA 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 (1) second. In total over 300 BOF parameters are sampled and logged in real time. Both historical and real-time plots of the data are made available to the operator. Off-gas data, process data as well as EFSOP® system alarms are emailed to TGI's office in Mississauga Canada allowing process engineers to follow the operation remotely.

Figure 2, is a plot of the measured composition and temperature of the off-gases for a complete heat. The plot is very typical and varies little with respect to pattern from one heat to the next. In general, the measured temperature hovers between 1600 and 1800 degrees Kelvin for most of the heat with a sharp decrease at the end of the heat (as carbon is depleted, and combustion in the fume system ceases). Complete combustion has been observed for all heats as there effectively no hydrogen or carbon monoxide in the off-gas at the downstream location. At the start of the heat, carbon dioxide ramps upwards as the lance is lowered and decarburization is initiated. Near the conclusion of the heat, the carbon dioxide falls rapidly as carbon is depleted. The pattern is mirrored in the oxygen curve.

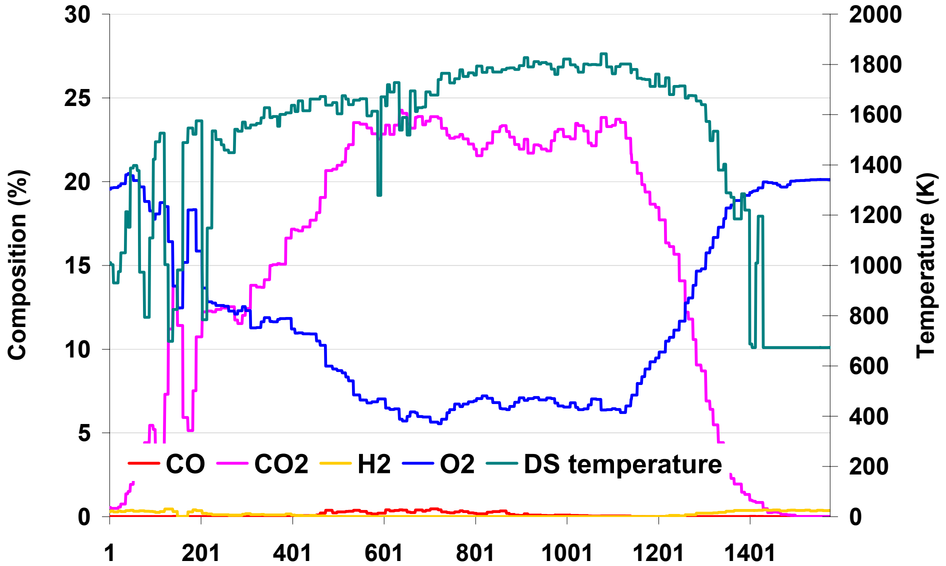

Figure 2. Profile - measured downstream off-gas composition and temperature for a typical heat.

2 End-Point Detection

A primary objective in oxygen steel-making is to achieve the desired turn-down temperature and grade chemistry at the lowest cost and shortest possible time. To do so, operators rely on standardized BOF practices and charge calculation models to operate their BOF. These charge models are static mass and energy balances. Initial conditions (scrap and hot metal temperature and composition) and desired end-point conditions of the bath and slag are used to calculate the total oxygen and fluxes required. These calculations are used, not only to define the operating practice, but also as an indication of when the desired end-point is expected with respect to the total amount of oxygen blown into the steel bath.

In practice, charge models are limited in the ability to accurately predict end-point because they do not take into account the dynamics of the process over the course of the blow. End-point accuracy is also affected by uncertainties in the inputs (e.g. initial temperature, mass and composition of the hot metal). In BOF steelmaking, operators typically use their charge model as a guide to signal the end of the blow. Other cues, such as the change in the color of the flame at the mouth of the BOF and a characteristic drop in the steam temperature in the fume system cooling panels may also be used as indicators of when carbon in the steel bath has been depleted.

Due, in part to the difficulty in predicting end-point carbon, some plants do not operate a “catch-carbon” practice. That is, they aim to achieve temperature and phosphorus end-point and typically over-blow the heat with respect to carbon and then re-add carbon back into the ladle. A heat is stopped when the oxygen consumption has reached the level indicated by the charge model. At that point the operator turns down the vessel and takes a measurement of temperature. A sample of steel is also taken and sent to the lab for analysis. Tapping is initiated if the heat meets grade. If the heat is low in temperature or high in carbon, the vessel is returned to the blowing position and oxygen blowing is re-initiated. In some cases, a second, or even third "turn-down" may be required.

A review of a typical practice reveals many inefficiencies and opportunites for optimization given the subjective nature of end-point determination. For example, at one plant, reblows occur for approximately 13% of their heats. As indicated in figure 3, 60% percent of reblows are due to temperature and carbon while 32 % are attributed to meeting phosphorus specs. The remaining 7% are due to Meltshop logistics; for example, delays downstream of the BOF may require that a heat is held for a period of time. In that case, the may required re-blowing to re-increase the temperature before tapping.

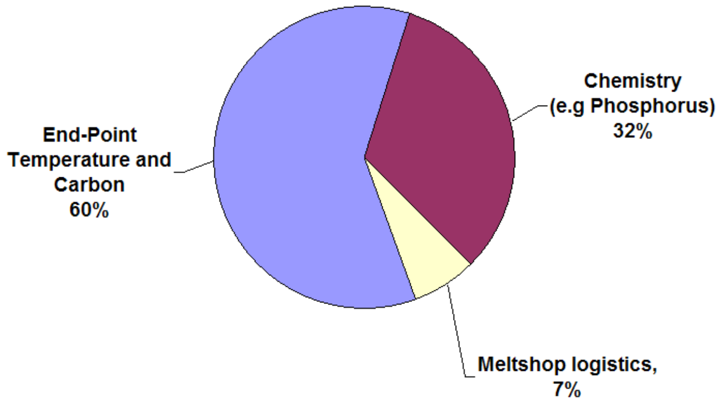

Figure 3. Typical distribution for the attributed cause of reblows.

Losses in potential productivity aside, turn-downs dramatically affect yield. As indicated in Figure 4 below, it is estimated that each turn-down corresponds to a loss in yield of approximately 1.5%.

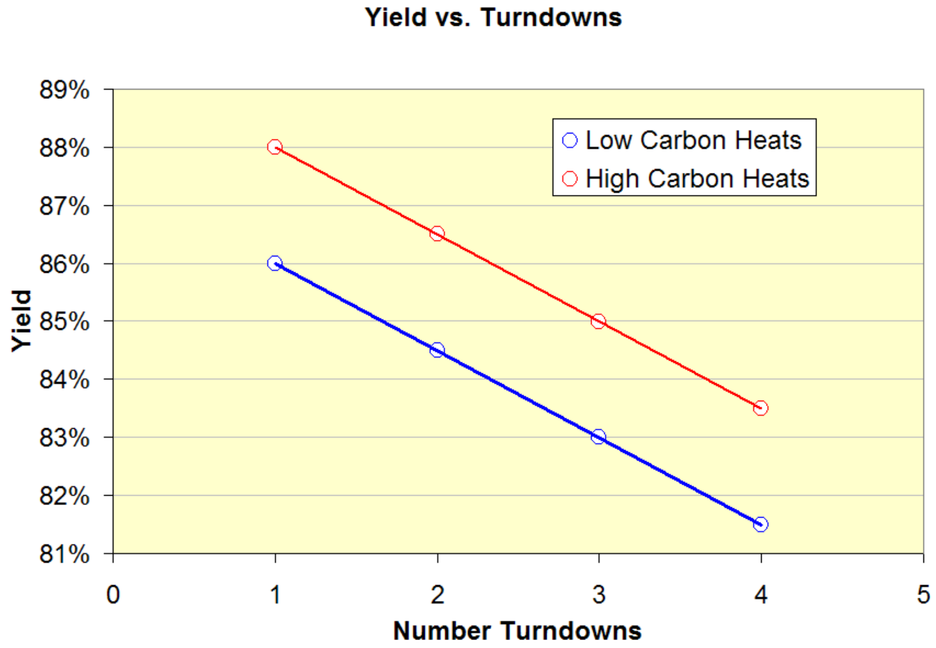

Figure 4. The affect of turndowns on yield for high and low carbon heats.

Various methods for end-point detection are presently being used through-out the oxygen steel industry; with mixed effectiveness. A common theme throughout the methods is the practice of sampling the bath at near-end and concluding the heat according to intermediate measurements of bath composition and temperature. Dynamic models of the decarburization reaction are used to complete the heat and to determine the end-point. The effectiveness of these practices depends on the accuracy of the dynamic models and the ability to accurately model the kinetics of the decarburization reactions.

Kinetics of decarburization is 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%), the mass transfer rate is high enough that the rate of decarburization is controlled by the rate of oxygen supply to the steel bath. At low carbon concentrations, the rate of mass transfer is insufficient to react with all of the injected oxygen and so the rate of decarburization is governed by the rate of carbon diffusion to the reaction interface.

The EFSOP® strategy for end point prediction builds upon the common practice of using charge models and dynamic models to predict and gauge end-point with one fundamental improvement; this being the use of dynamic, real-time off-gas composition to improve the predictive ability of the process models.

3 Dynamic Modelling of the BOF

The ability to predict end-point accurately relies on a reliable dynamic model of the BOF process and the ability to elucidate from the analysis of the off-gas the properties of the bath and slag over the course of the heat. Static models assume that either all of the blown oxygen participates in bath/slag reactions, or assume a constant oxygen efficiency factor to account for a fraction of the oxygen that does not participate in the bath/slag reactions; but instead goes to post-combustion of CO in the free volume of the BOF vessel. In actuality, the fraction of blown oxygen attributed to post-combustion (and therefore does not participate in bath/slag reactions) varies not only from heat to heat, but more importantly over the course of the heat. Changes in the lance efficiency are not unexpected and are affected by a variety of influences such as lance wear, variations in the height of the lance, etc.

The relative lance efficiency is calculated by defining a control volume encompassing the gas phase within the free volume of the BOF as shown in Figure 5. An oxygen balance over this volume gives the total rate of oxidation (carbon, silicon, etc.) A carbon balance gives the rate of decarburization. The difference between total oxygen going to oxidation, and oxygen returned to the control volume as carbon monoxide is the rate of oxide formation (FeO, SiO_2, etc.). The calculation is performed dynamically over the course of the heat and depends on knowing the composition (O_2, CO, CO_2) and the absolute rate of off-gas leaving the mouth of the vessel.

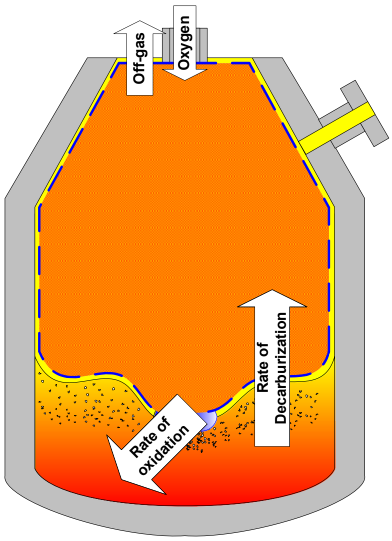

Figure 5. Control volume of the freeboard control board.

To this end, a second control volume is defined as illustrated in Figure 6. With respect to this second control volume, balances for carbon, oxygen and nitrogen make it possible to calculate the fractions of air and off-gas corresponding to the measured downstream composition (provided by EFSOP® analyzer). The assumption of thermodynamic equilibrium and the measured off-gas temperature at the combustion gap gives the composition of the off-gas leaving the mouth of the BOF vessel.

Finally, an internal energy balance (Bernoulli's method for flow calculation), provides a relationship for total flow rate. The static pressure at the downstream location is measured and the density, calculated. The flow calculation is affected by pressure losses, and so the relationship is tuned by numerical integration of total carbon leaving the BOF; where total carbon is given by the difference between starting carbon in the hot metal and the final carbon at tap.

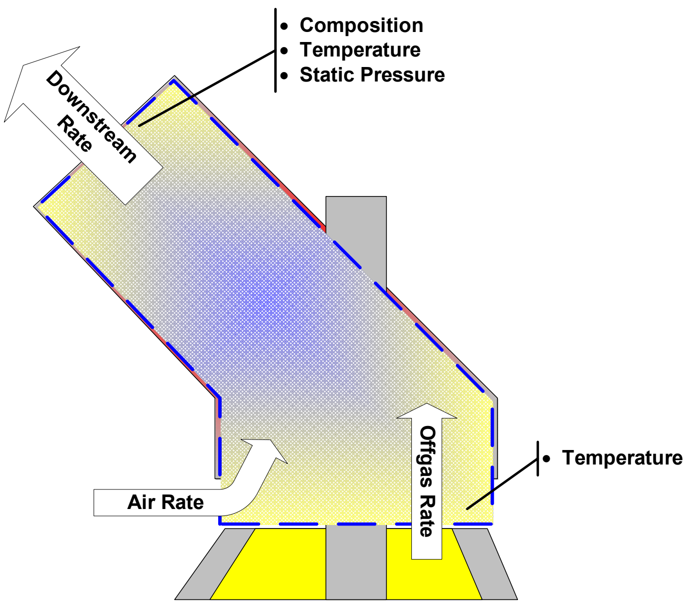

Figure 6. Downstream control volume.

4 Preliminary Results

The model, based on real-time dynamic measurements (and not assumed) off-gas composition and temperature, provides important dynamic information about the steel making process. For instance, the molar rate of off-gas leaving the mouth of the vessel, along with the molar rate of air entering the combustion gap is shown in Figure 7. The figure illustrates a common pattern noted wherein the off-gas rate increases once the majority of the species with higher affinity for oxygen than carbon (e.g. Si, Mn, etc.) have been oxidized. At the end of the heat, as carbon is almost depleted, the decarburation rate decreases, more FeO is generated and consequently the off-gas flow rate decreases sharply. The rate of air entering the fume system at the combustion gap is also related to the rate of off-gas drawn from the vessel. As the off-gas rate and temperature increase, the rate of air entrained through the gap decreases.

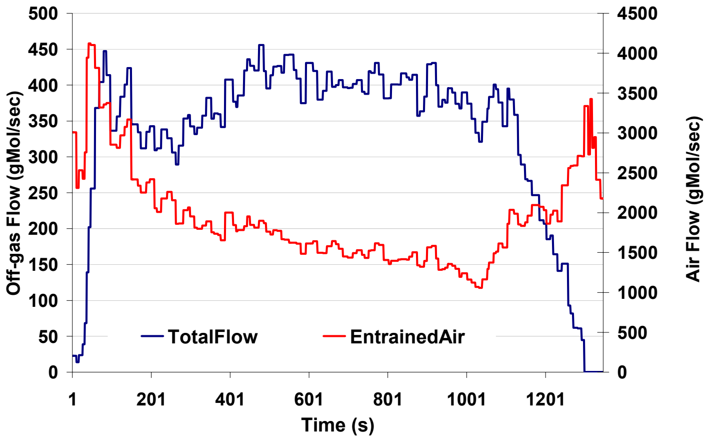

Figure 7: Off-gas and air rates, calculated downstream of the combustion gap.

The composition of the off-gas at the mouth of the vessel is calculated based on the assumption of equilibrium and measured temperature at the mouth of the vessel. The fraction of air in the downstream sample is accounted for by a nitrogen balance. The result for a typical heat is shown in Figure 8. As illustrated, the concentrations of CO and CO_2 are not constant over the course of the heat; varying instead between 75% to 85%, and between 15% to 25%, for CO and CO_2 respectively.

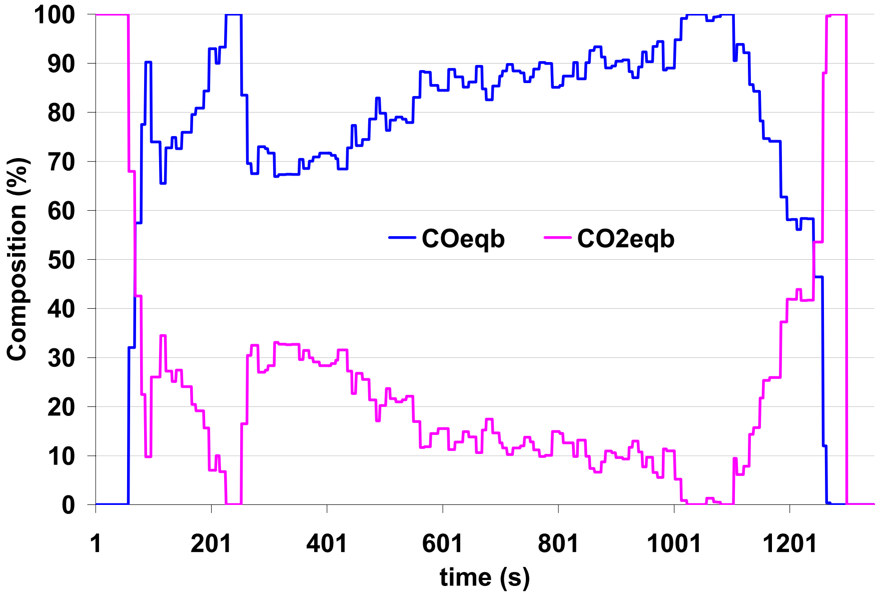

Figure 8. The composition of off-gas leaving the mouth of the BOF vessel.

The rate and composition at the mouth of the vessel, along with a balance of carbon and oxygen taken over the free volume of the BOF vessel permit the calculation of the rate of decarburization, oxidation (slag formation) and post-combustion inside the vessel. Results for a typical heat are provided in Figure 9. The plot is stacked to show the relative fraction of the total blown oxygen that can be attributed to decarburization, post-combustion and oxygen going for slag formation. Note that although the rate of oxygen injection remains fairly constant over the course of the heat, the relative fractions do not. As expected, relatively large values for slag formation are noted at the start of the heat and at the end of the heat. The large spike at the start of the heat is attributed to the preferential oxidation of silicon.

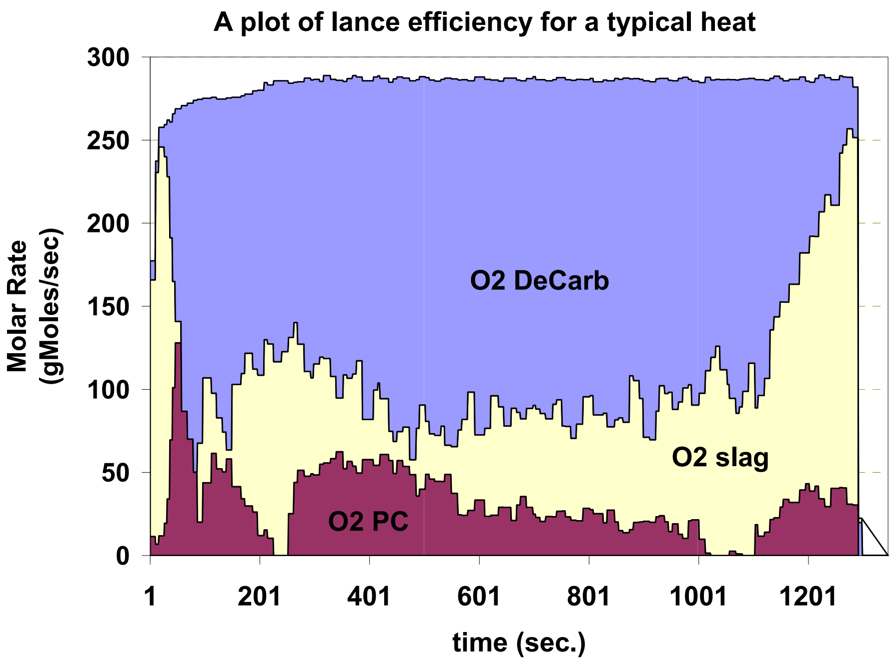

Figure 9. A profile of the oxygen distribution for a typical heat.

With the off-gas defined, the modeling effort is easily extended to the steel. An energy balance of the bath and slag, along with the carbon and oxygen balances of the off-gas, allow the calculation of temperature and carbon content of the steel. Some preliminary results are provided below.

Figure 10 is a plot of the predicted temperature is plotted against the actual temperature. The standard deviation between the predicted and measured temperature (at first turn down) is 23 degrees Celsius.

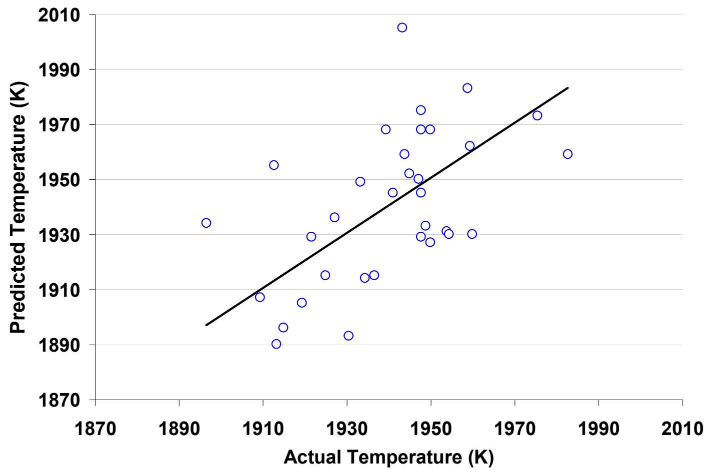

Figure 10. The correlation between predicted and actual temperature

Figure 11 is a plot of the distribution of the statistical error made in the prediction of carbon (calculated as the difference between measured and predicted carbon). Notice that, for 75% of the heats, the error of the carbon prediction compared with the measurement is lower than 0.009 points percent. These results are preliminary and are expected to improve even further with fine-tuning of the models.

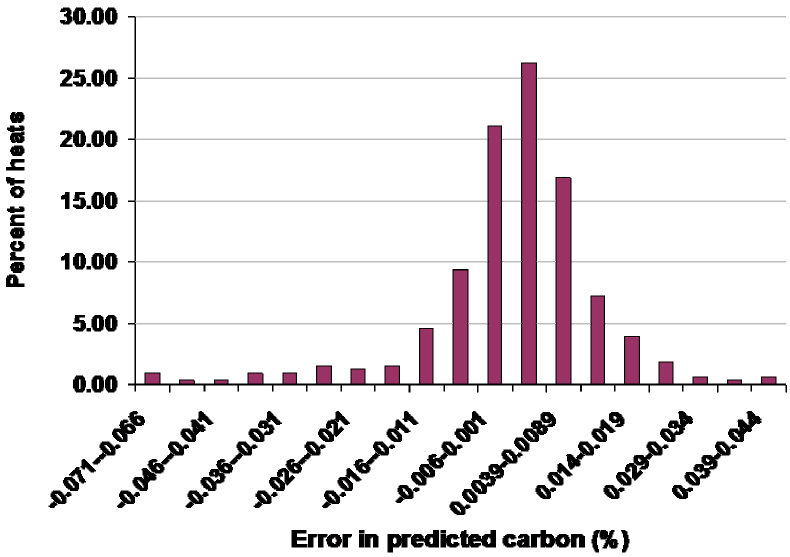

Figure 11. Distribution of the error for end-point carbon.

5 Conclusions

An off-gas based system for end-point prediction has been discussed. Work is ongoing but positive results have been achieved to date in both carbon and temperature end-point.

The prediction of end-point temperature has been evaluated off-line and the results presented in section 4 above. The standard deviation of predicted end-point temperature is 23 degrees Centigrade. The results are in-line with those reported by Chukwulebe et. al.[10] in his review of ArcelorMittal Steel end-point prediction throughout their organization. In their review, ArcelorMittal has been able to reach better end-point prediction of temperature only in installations with sublance and bomb sampling near the end of the heat.

The prediction of end-point carbon has also been evaluated off-line and the results presented in section 4 above. Chukwulebe et. al., for the ArcelorMittal group report a range of standard deviations for carbon end-point spanning 0.008 – 0.0128 percent for eight of the shops investigated. The off-gas based prediction of carbon end-point fall at the low end of this scale with 75% of the heats falling within 0.009 percent of the measured end-point.

Going forward, the models will be further tuned in order to improve already reasonable end-point prediction of temperature and carbon. A remaining deliverable for end-point prediction is phosphorus prediction. Efforts are expected to provide a dynamic indication of the steel and slag composition over the course of the heat. Offline validation of the results are promising and so the end-point prediction modules for temperature and carbon will be put on-line with trials scheduled in the next coming weeks. As temperature and carbon account for most of the reblows, the model is expected to have a significant affect in the reduction in the number of turndowns and subsequently yield.

It has also been noted that the predictive ability of the model is greatly affected by deviations from the typical rate of oxidation and decarburization observed for most heats. It is the occurrence of these outlier heats that make end-point prediction challenging. Fortunately, the off-gas analysis provides a clear indication of periods when decarburization or the rate of oxidation has deviated from the norm. It is expected that the variability in achieving end-point conditions can be greatly reduced by implementing dynamic control of the lance height and flow in feed-back response from the off-gas analysis and models.

A second phase of the SDTC project will be the implementation of a dual-stream flow lance for controlled post-combustion inside the free volume of the BOF vessel. The plan is to control post-combustion in response to measured off-gas composition. The generation of additional energy, via post-combustion, inside the BOF has the expected benefits of allowing the steelmaker to increase the ratio of scrap to hot metal.

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