i EAF® TECHNOLOGY: RECENT DEVELOPMENTS AND RESULTS[1]

Steven Gillgrass [2]
Vittorio Scipolo [2]
Armando Vazquez [3]

Abstract

Tenova's *i*EAF® is an innovative system with the aim of dynamic control & optimization of the EAF. It incorporates off-gas analysis with the addition of continuous process measurement tools and detailed online models. Measurement tools & process models allow for a holistic approach to EAF optimization from the mass balance and energy balance sides. Details on the installation of instrumentation and hardware used to improve the measurement of off-gas flow and calculation of other variables is described as well as further changes to process modeling and dynamic measurement. Results from initial control and optimization trials on combustion control and results from chemical and thermal endpoint prediction are reported. Conclusions and future work, including further instrumentation and hardware additions, are also presented.
Keywords: Off-gas analysis; Mass and energy balances; Process control; EAF steelmaking.

TECNOLOGIA *i* EAF®: DESENVOLVIMENTOS RECENTES E RESULTADOS

Resumo

O *i*EAF® é um sistema inovador para o controle dinâmico e otimização do FEA. Ele incorpora a análise de gases de exaustão com a adição de ferramentas de medição contínua de processo e modelos online detalhados. Ferramentas de medições e modelos de processo permitem uma aproximação holística à otimização do FEA pelo balanço de ambas massa e energia. São descritos detalhes da instalação de instrumentação e hardware adicionados especificamente para melhorar a medição do fluxo de gases de exaustão e cálculo de outras variáveis, assim como outras modificações no modelamento do processo e medição dinâmica. São relatados resultados de testes iniciais de controle e otimização do controle da combustão e resultados da previsão do ponto final químico e térmico. Também são apresentadas conclusões e trabalhos futuros, incluindo a adição de instrumentação e hardware.
Palavras-chaves: Análise de efluentes gasosos; Balanço de massa e energia; Controle do processo; Fundição de aço EAF.

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2 *Technology & Development, Tenova Goodfellow Inc.*
3 *Sales & Marketing, Tenova Goodfellow Inc.*

Tenova's *i*EAF®: Concept and Technical Overview

The "Intelligent Electric Arc Furnace" (*i*EAF®) is an innovative automation system developed for the dynamic control and optimization of the electric arc furnace that is based on the real-time measurement of off-gas composition, dynamic process inputs and online process models. Technical details about the concept and design, as well as initial results, have been previously described [(1)]. The purpose of this paper is to provide an update regarding the installation of *i*EAF® at TenarisDalmine.
Conceptually, the components of the *i*EAF® are shown in Figure 1 where each layer builds upon the previous to form the system. Specifically, the layers of the *i*EAF® are:

- Sensors and Instrumentation
- Dynamic Process Models
- Control and Optimization Modules

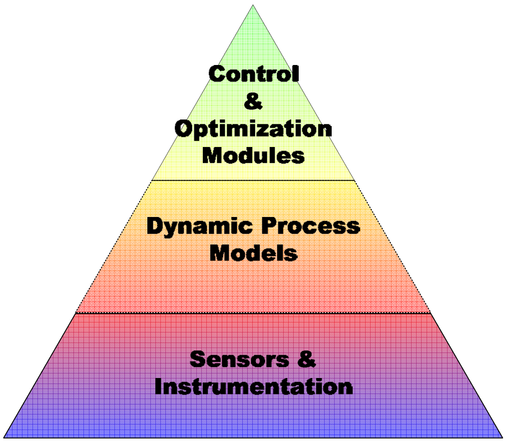

Figure 1 – The *i*EAF® conceptual pyramid.

Online sensors and the integrated mathematical models provide fundamental process knowledge that allow for advanced control of the electric arc furnace process. Process models extend the primary information to provide process information that is used to control the EAF.

Sensors and Instrumentation

A basic schematic of some of the sensors that make up the *i*EAF® is shown in Figure 2. The EFSOP® probe is located just downstream of the combustion gap and positioned such that the tip extends into the cone of gases leaving the EAF. This ensures that the off-gas sample is acquired before dilution and combustion with air entering the combustion gap and is therefore representative of the gases inside the furnace. The gases are analyzed on a dry basis for CO, CO_2, H_2 and O_2.

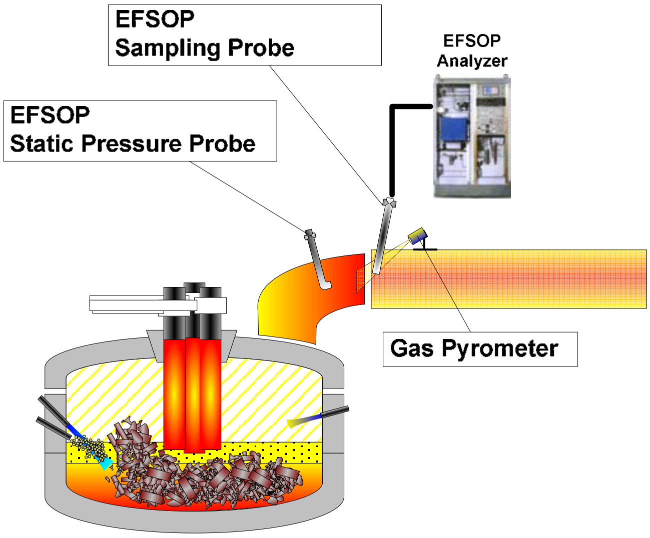

Figure 2. A schematic of the basic *i*EAF® sensors.

Automation and control of the electric arc furnace (EAF) is limited by the many challenges associated with implementing reliable, low-maintenance process sensors in the harsh environment. At the base of the *i*EAF® pyramid are the sensors and instrumentation that form the foundation of the *i*EAF®. The system includes:

- A patented, water-cooled sampling probe; a heated sample line; and the EFSOP® analyzer for sampling, conditioning and analyzing the furnace off-gas
- Infrared gas pyrometer that measures the temperature of the off-gas at the location of the EFSOP® sampling probe
- Static pressure probe located on the roof or 4th hole elbow of the EAF
- Various thermocouples and flow meters for determining temperatures and flows of water cooling

In addition to the above instrumentation there are a number of other sensors that are currently in development and could potentially become part of the *i*EAF® package. These include:

- A system for determining the height of the liquid heel and slag at the start of the heat
- Weigh cells to provide a dynamic indication of the furnace weight
- Continuous flat-bath temperature measurement via pyrometric methods

The system installed above the EAF for determining the height of the liquid heel and slag heel at the start of the heat, reported to be in development,[1] has been abandoned due to continued damage from the heat during charging. As a replacement, another method of measurement is in development. Currently hot heel and slag heel are determined based on the mass of steel and slag calculated by the process models during the heat and corrected when the tapping weight is measured. Manual corrections are made when the value deviates from what is observed in the EAF. This sensor will be used to evaluate the bath level and is intended to enhance the hot heel and slag heel calculation by constraining the results so that any deviation can be corrected by the process models.
Two significant additions have been added to the sensors and instrumentation of the *i*EAF®. The first is a sensor for determining the mass flow rate of slag that is leaving the electric arc furnace during melting and refining. The sensor measures the slag

exiting the EAF, along with statistical techniques, to calculate the real-time mass in the EAF, thereby continuously updating the process models and aiding in the calculation of the mass and energy balances.

Figure 3 shows the change to the hot heel and the slag heel values in the EAF across a campaign. The trend for both hot heel and slag heel are very good and consistent over multiple heats. Due to the variation in hot heel and slag heel, accurate calculation of hot heel mass is necessary for both the mass and energy balance of the EAF.

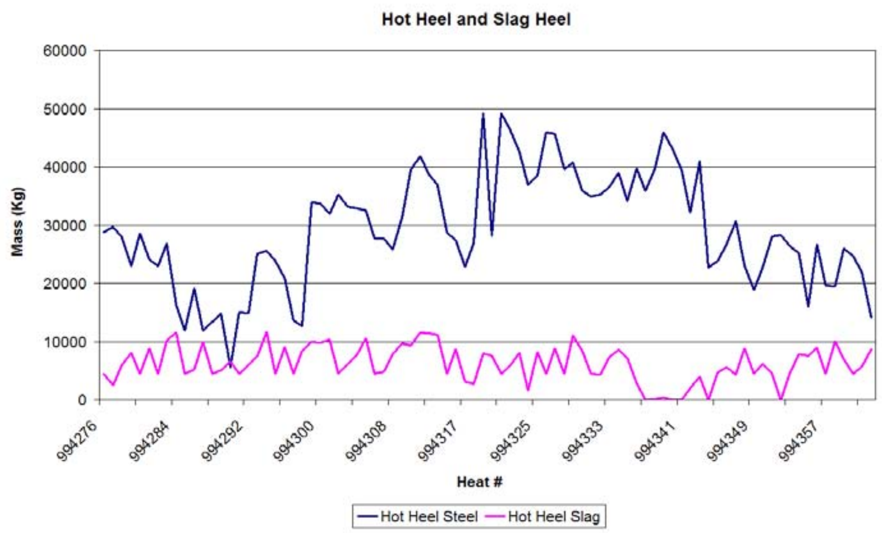

Figure 3. Hot heel and slag heel values across a campaign.

Figure 4 shows the mass of deslagging from a recent campaign. It can be seen that the mass of slag leaving the electric arc furnace varies significantly from heat-to-heat. In order to achieve a true dynamic model for on mass and energy balances, the real-time slag mass and must be considered.

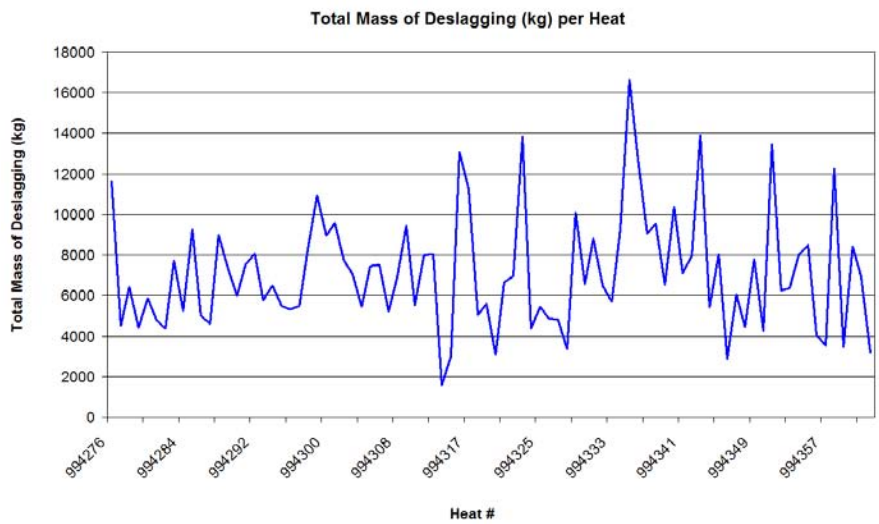

Figure 4. Total mass of deslagging per heat as measured by the ***i***EAF®.

The second addition to the sensor and instrumentation package is a downstream off-gas analysis system. The downstream system measures downstream gas composition, velocity and temperature. This information is used to calculate off-gas flow from the electric arc furnace by using a carbon balance between the off-gas composition at the elbow and at the downstream location. At TenarisDalmine, there is a scrap preheating system, so two thermocouples and velocity sensors were installed.

Off-gas flow is one of the most critical dynamic aspects of the energy balance of the electric arc furnace and one of the key aspects of Tenova's *i*EAF®. Figure 5 shows a graph of off-gas flow using three different methods of calculation. The first method is the calculation based on the carbon balance provided by the new downstream analysis system. The second method is the calculation based on the pressure and temperature at the 4th hole elbow. The third method is a static value of 210 moles/sec based on an average from previous off-gas flow measurements in the duct. The measurement of static pressure at the 4th hole elbow requires more tuning and is less dynamic as it is based on constants determined during in situ testing of off-gas. While accurate, these constants do not compensate for changes to ambient conditions or changes in the duct system outside of the time the measurements were taken. It is important to note that travel time between the two analysis systems, as well as any time delay for analysis has been considered, but does represent a margin of error in the calculation. To compensate for this margin of error, usually related to quick changes in pressure or slightly off-set composition information, off-gas as an input to the *i*EAF® process models is expressed as a moving average.

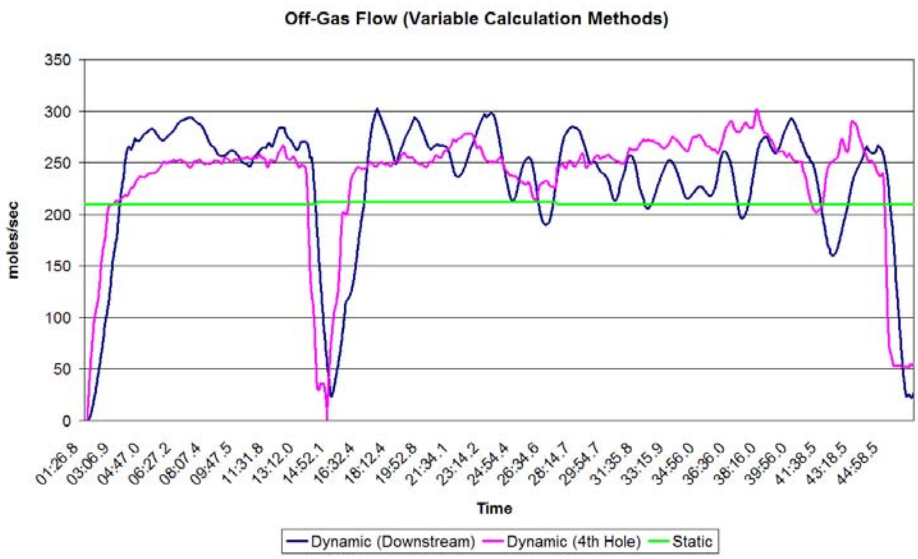

Figure 5. Comparison of off-gas flow calculation methods across 1 heat.

Table 1 shows the percentage difference using the three methods for the same heat for each method of calculation. The values for off-gas volume during power on time vary between the two dynamic methods and it is clear that static values are insufficient for proper characterization of off-gas glow.

Table 1. Comparison of off-gas flow calculation methods

	% Difference vs. Downstream	% Difference vs. 4th Hole Elbow	% Difference vs. Static
Dynamic (Downstream)	--	-2.1%	11.0%
Dynamic (4th Hole Elbow)	2.1%	--	12.9%
Static	-11.0%	-12.9%	--

Results of the *i*EAF® at TenarisDalmine

TenarisDalmine, located in Dalmine, Italy, has running the first installation of Tenova's *i*EAF® since late 2008. There have been many challenges over this time, but during recent campaigns, the sensors, process models and control modules have been tuned significantly and have been running with a good level of stability. In addition to the new sensors described above, many changes have been made to calculation methods within the process models and control modules. As a direct result of the data that has been collected from *i*EAF®, it has been possible to better tune many of the inputs into the process models by constraining them to realistic values. This helps to ensure that tuning and control activities are not delayed when maintenance or other delays occur. Some of the measured dynamics of the EAF will be shown to display how *i*EAF® is capturing the true dynamics of the electric arc furnace process.

As previously described, the *i*EAF® process models calculate both mass & energy balances for the electric arc furnace freeboard using dry off-gas composition along with other thermodynamic inputs. With these inputs, it is possible to calculate the "wet" composition of the off-gas leaving the electric arc furnace through the 4th hole. Figure 6 shows an example of the average "wet" composition calculated by *i*EAF® across heats from a recent campaign.

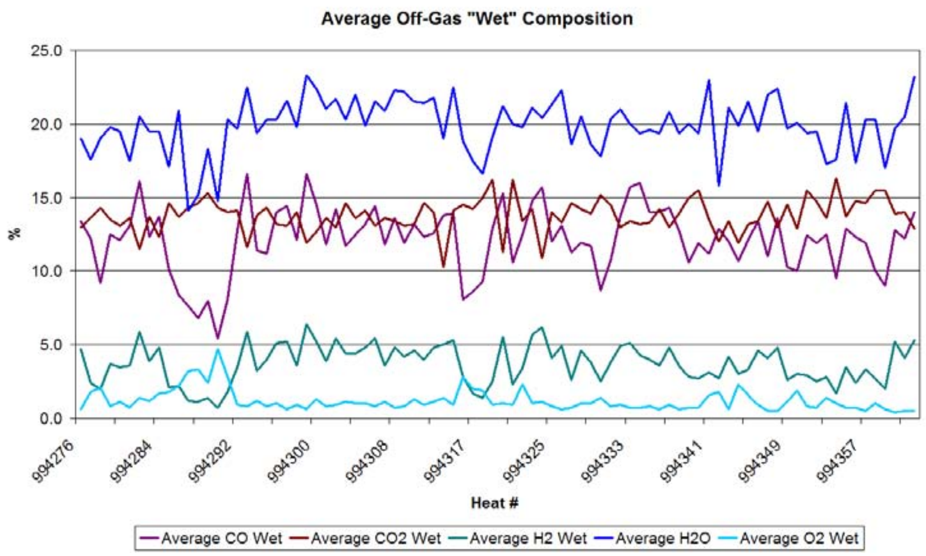

Figure 6. Average off-gas wet composition across a campaign.

With the composition of the off-gas leaving the EAF, a mass balance can be applied using nitrogen and hydrogen to calculate the rate of water and air entering the freeboard volume. The results are presented in Figure 7. While there are still some significant spikes relating to off-gas flow and as a result total water and total air, the tuning of *i*EAF® to the operation at TenarisDalmine is showing the dynamic aspect of off-gas flow and composition. Some discussion in Conclusions and Future Work below will address the next steps being taken to improve the consistency of the freeboard model calculation.

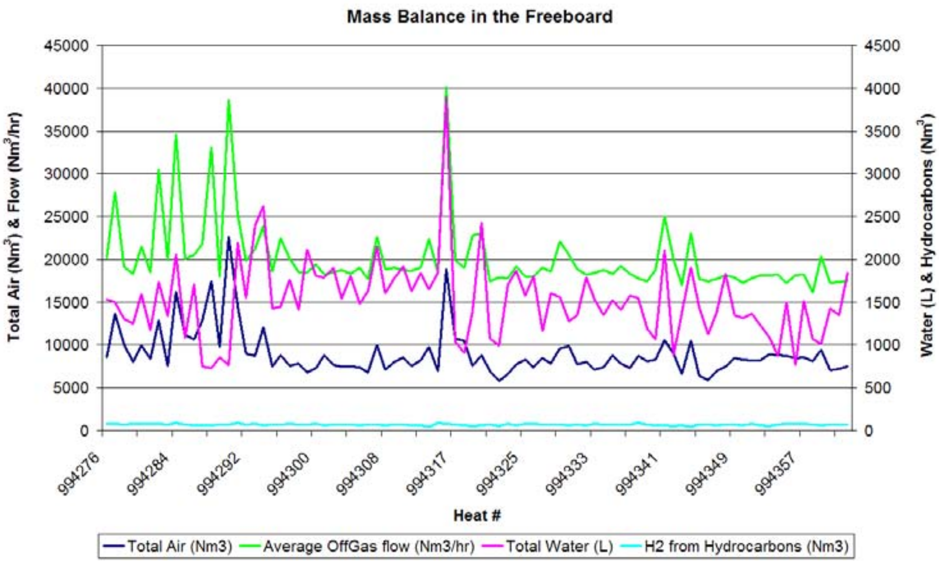

Figure 7. Mass balance in the freeboard for air, water, and hydrocarbons.

One of the key aspects of leveraging off-gas analysis composition and temperature measurements is the ability to determine the heat losses in the off-gas. While many plants measure the heat losses to the roof and shell, off-gas losses remain a significant unknown in the mass and energy balances of the EAF. Figure 8 shows the heat losses from the electric arc furnace over a campaign of heats. While there is still some variation in the results (as evidenced by some large peaks in the graph), the off-gas losses are being characterized well across the campaign.

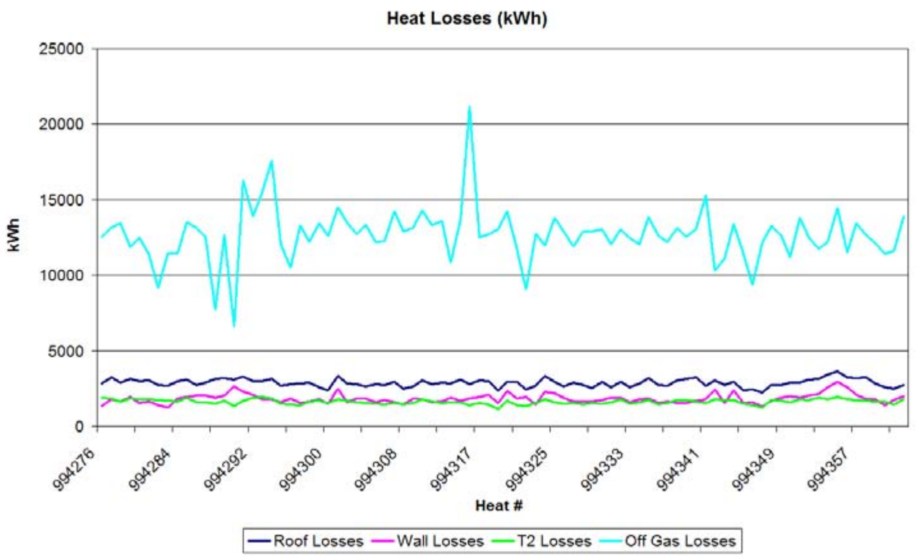

Figure 8. Heat losses from the EAF across a campaign.

In determining total heat losses, it is possible to calculate the total net energy that is supplied to the scrap and other materials in the EAF. Using total net energy allows for the calculation of melting progress, where the net energy that is supplied to the scrap can be used to determine the extent of heating and melting that is taking place in real-time. Figure 9 shows the total available energy in comparison to the total electrical energy supplied to the electric arc furnace. Total available energy takes into account the losses that occur to the off-gas and water cooling in the EAF and as expected, variation is directly related to total electrical energy, but also shows significant variation from heat-to-heat.

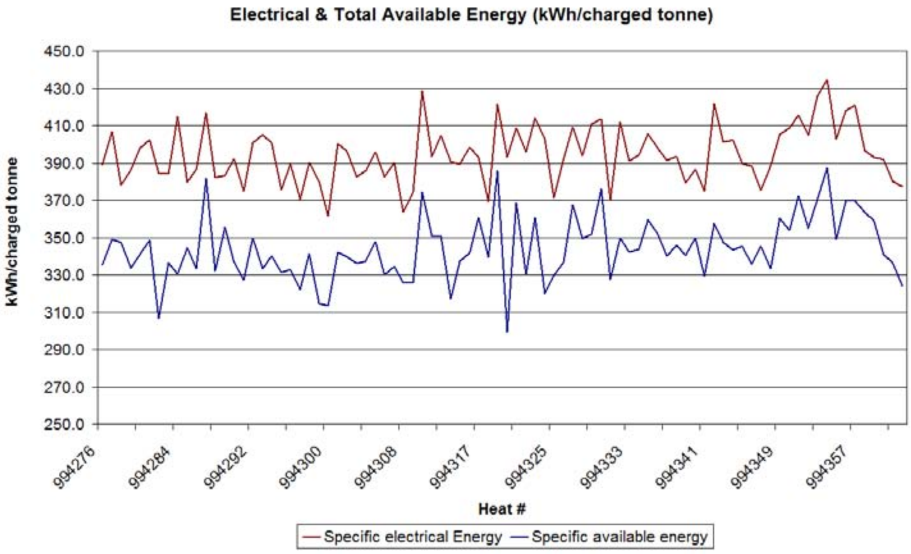

Figure 9. Comparison of Total Electrical and Total Available Energy.

Typically, delivery of chemical energy to the EAF is based on fixed profiles defining oxygen, fuel, carbon and lime injection set points. These profiles are usually a function of the electrical energy supplied to the EAF (kWh or kWh/t). An issue, from the operational point of view, with this strategy is that the rate of electrical energy delivery does not include the heat losses due to water cooling and off-gas. As the EAF process has become more dependent on chemical energy than before, there is not the same direct relationship between electrical energy and the melting process. Today, heat progress is a stronger function of total net energy (electrical plus chemical) supplied to the furnace; and not electrical energy alone. The *i*EAF®, using off-gas composition, considers the total net energy (including actual chemical energy evolved in the furnace) to calculate melting progress.

Figure 10 shows the melting progress vs. specific electrical energy across several consecutive heats. This graph shows the true potential of controlling the EAF using total net energy as opposed to total or specific electrical energy. In the graph, note that for equivalent specific energy there is a difference in the melting progress for each heat. This is due to changes in the melting efficiency that are not considered when using specific electrical energy. Also note on the graph, the points where melting progress achieves 100%. At this point, the mass (scrap and fluxes) in the furnace has received enough energy to become completely liquid. Again, there is a large variation in the specific energy required compared to the melting progress. Due to variation in scrap melting efficiency (changing scrap quality and sizing, amongst other factors), specific electrical energy cannot sufficiently characterize the melting process. Figure 10 shows that using total net energy as a process parameter to evaluate and control auxiliary equipments on the EAF can result in reducing the inefficiencies associated with heat-to-heat variations.

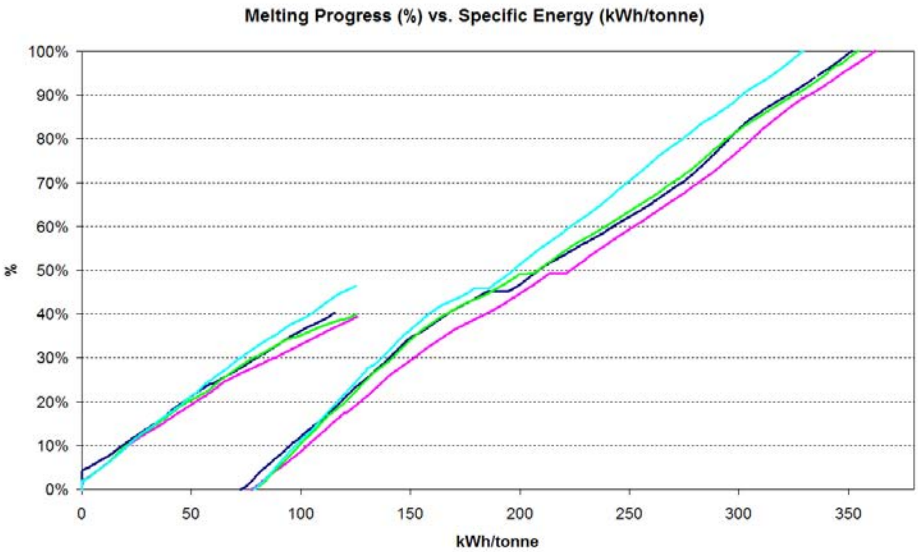

Figure 10. Melting progress vs. specific energy across several heats.

With the calculation of melting progress based on the total net energy, control of the oxy-fuel burners has been tested. During this testing period, the burner program was set to match the existing burner program at TenarisDalmine, and set points were established that would match the static set points of the existing burner program, but still vary based on the differences between total net energy and specific electrical energy. Burner control has been tested on multiple occasions with positive results. Table 2 shows the results from the most recent control campaign. The results are displayed as percent savings compared to a baseline set of heats, considering the same power program and scrap recipe.

Table 2. Results of Burner Control Testing

	Control Trial
Methane	2.57%
Oxygen	2.61%
Energy	0.47%

The culmination of *i*EAF® is the ability to determine bath & slag composition and temperature in real-time. This information allows the operator to make key decisions during refining where time and productivity can be easily lost. There is still deviation between the measured value of the plant and the predicted value from *i*EAF®. Some of this variation can be described as outliers, but there is still work on-going to better understand the difference between the *i*EAF® prediction and the measured result. Over short runs (between 10 and 30 heats), the predicted temperature averages close to zero degrees with a standard deviation of 5 - 25 degrees. Over longer campaigns (> 50 heats), the temperature prediction has been performing at an average value centered near zero degrees, with a standard deviation of 30 – 40 degrees.

Figure 11 shows the average slag composition across a recent campaign. The slag composition calculation is reacting very well to levels of decarburization and oxidation. However, there is still work to be done to ensure consistency, specifically in the amount of oxygen that is being supplied to the process models.

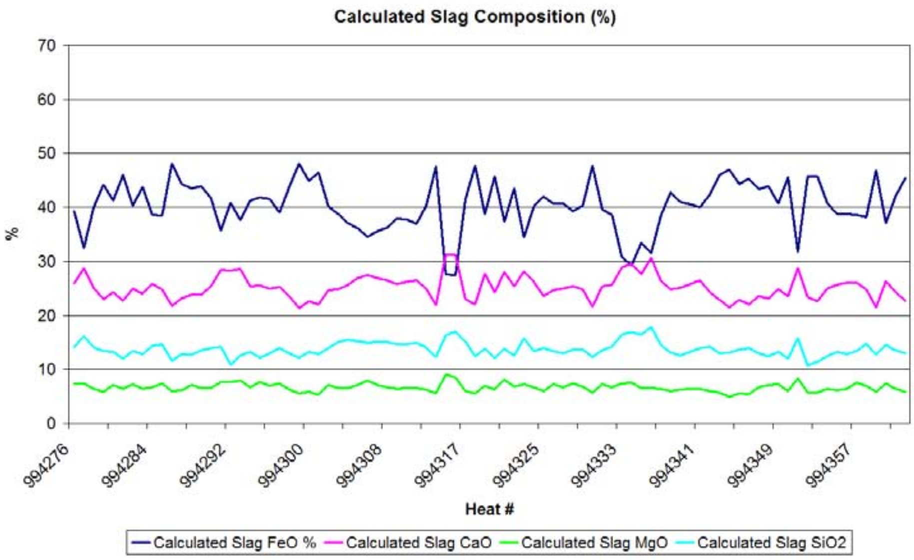

Figure 11. Calculated slag composition.

Conclusions and Future Work

Recent campaigns at TenarisDalmine have shown that ***i***EAF® is characterizing the dynamics of the electric arc furnace process. Results from these campaigns show good consistency with respect to the values that are being measured and calculated. There is still work to be done to tune this program and to analyze the results to ensure accuracy across multiple campaigns under changing conditions. Recent sensor and equipment installation has improved the accuracy, but more is to be accomplished.

Installation of a camera for measuring deslagging and downstream analyzer system for measuring off-gas composition have yielded significantly improved results with respect to the mass balance inside the EAF and characterization of off-gas flow from the EAF. With the accuracy of these measurements, the dynamics of the EAF process have become easier to model and have shown very good consistency across a number of campaigns.

The first control module (combustion control of oxy-fuel burners) has been tested using the total net energy to determine the set points. The tests yielded favorable results and more testing is planned across a much larger number of heats to determine the savings of controlling the oxy-fuel burners based on this value.

Specifically related to improvement of the wet composition calculation, one of the key challenges is to accurately determine the water content in the off-gas since the EFSOP® and downstream analyzer provide only dry composition for CO, CO_2, H_2 and O_2. Original tuning and calculations were focused on determining water content solely on the water-gas shift reaction at assumed equilibrium temperature. Recent tuning and model upgrades have approached the water content calculation as a mass balance where known sources of water (specifically electrode cooling sprays and hydrocarbons/oils in the scrap charge) are considered. Some modifications to the models are still to be made, but it is expected that this approach will improve the calibration and reduce the variability of the models

Further study of the off-gas flow and chemistry is necessary to accurately detail the oxidation that is passed from the freeboard process model to the bath/slag process model. Specifically related to inconsistencies with end point temperature, the oxidation level tends to be higher than expected over numerous heats. This means that the model is considering too much air entering the freeboard or too much of the oxygen content of the air entering the freeboard is being passed to the bath/slag model.

Reference

1 MAIOLO, J.A.; SCIPOLO, V; CLERICI, P.; "*i*EAF® Technology: Dynamic Process Control for the Electric Arc Furnace", AISTech 2009, Volume I, Pittsburgh, PA USA, May 2009, p. 565-576.