i EAF® TECHNOLOGY: DYNAMIC PROCESS CONTROL FOR THE ELECTRIC ARC FURNACE (INCLUDING WATER DETECTION)[1]

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Abstract

The *i* EAF® is an innovative automation system for the dynamic control and optimization of the electric arc furnace (EAF), that is based on continuous, real-time process measurements and online process models. Building upon the EFSOP® real-time off-gas analysis system, the *i* EAF® is an extension of Tenova's holistic approach to EAF control and optimization. Process models have been developed to calculate complete mass and energy balances of the solid, liquid and gas phases of the furnace. These provide crucial steel-making information such as: net energy to the metallic charge; a measure of the extent of melting; and bath and slag composition and temperature. An innovative feature of the *i* EAF® is the control and pacing of the EAF process according to the extent of melting instead of an electrical energy clock. The *i* EAF® provides increased productivity, improved economical performance through reduced conversion costs, reduced process variability, environmental benefits, increased process knowledge and enhanced safety. The dynamic mass & energy balance provides the direct calculation of the rate of water entering the furnace freeboard. A statistical profile of normal water rates can be determined and used as a baseline for comparison. Severe deviations from the baseline are indicative of a possible water-leak in the furnace. This paper will outline the main components and features of the technology including results from the premier installation on a 100 tonne furnace. State-of-the-art process control technology, based on innovative sensors and process models, allows steelmakers to achieve "Intelligent EAF steelmaking" (*i* EAF®).

Key words: Off-gas analysis; Mass and energy balances; Process control; EAF steelmaking

TECNOLOGIA *i* EAF®: CONTROLE DO PROCESSO DINÂMICO PARA O FORNO A ARCO ELÉTRICO (INCLUINDO DETECÇÃO DE ÁGUA)

Resumo

O *i* EAF® é um inovador sistema de automação para o controle e otimização dinâmica do forno a arco elétrico (EAF), que é baseado em medições de processo contínuo em tempo real e modelos de processo online. Com base no sistema de análise de efluentes gasosos em tempo real de EFSOP®, o *i* EAF® é uma extensão do enfoque integral da Tenova para controle e otimização do EAF. Os modelos do processo foram desenvolvidos para calcular os balanços de massa total e energia das fases sólidas, líquidas e gasosas do forno. Estes fornecem informações cruciais da fabricação do aço, tais como: energia líquida para a carga metálica; uma medição do grau da fundição; e banho metálico e composição das escórias, e temperatura. Uma característica inovadora do *i* EAF® é o controle e gradação do processo EAF de acordo com o grau da fundição, em vez de um medidor de energia elétrica. O *i* EAF® oferece maior produtividade, melhor desempenho econômico através da redução dos custos de conversão, redução da variabilidade do processo, benefícios ambientais, aumento do conhecimento do processo e melhor segurança. O balanço da massa dinâmica e energia fornece o cálculo direto da taxa de água que entra na área de carregamento do forno. Um perfil da estatística da taxa normal de água pode ser determinado e usado como um parâmetro de comparação. Graves desvios do parâmetro são indicativos como um possível vazamento de água no forno. Este trabalho delineará os principais componentes e funcionalidades da tecnologia, incluindo resultados da instalação principal em um forno de 100 toneladas. A atual tecnologia de controle do processo, baseada em sensores e modelos de processos inovadores, permite que as empresas siderúrgicas alcancem a "fundição de aço EAF Inteligente" (*i* EAF®).

Palavras-chave: Análise de efluentes gasosos; Balanço de massa e energia; Controle do processo; Fundição de aço EAF

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1 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 EAF; that is based on the real-time measurement of furnace off-gas composition, dynamic process inputs and online process models. The *i* EAF® is the result of Tenova's holistic approach to EAF control and optimization that builds upon the EFSOP® real-time off-gas analysis system.

The benefits towards furnace control and optimization based on off-gas measurement using the EFSOP® system has been reported extensively in past years(1,2,3,4,5,6,7). Without off-gas analysis, operators have had to rely on static process information and highly simplified process models to operate and control their EAF's. The adoption of real-time off-gas analysis in the EAF has provided many steelmakers with a tool for understanding the dynamics of their process; but the benefits provided by off-gas analysis do not end there.

The *i* EAF® uses process models to determine, from the information provided by the available sensors (primarily off-gas composition and temperature) important steelmaking information; such as the rate of oxidation and the rate of decarburization. These direct calculations are in turn used to dynamically model the bath and slag. This information is indispensable for achieving process improvements and makes it possible to determine appropriate control actions on real-time process information.

EAF shops are equipped with a variety of different automation systems for controlling the EAF including electrode regulation, chemical package control systems and fume-system control systems. Seldom does one find a unified system to control the EAF and its auxiliary systems. The *i* EAF® is designed for this purpose, to bring together the control and automation of the furnace and auxiliaries under one automation umbrella. As a complete package, the *i* EAF® brings together all aspects of furnace operation. Feedback from the process, provided by various sensors (eg off-gas analysis; electrical harmonics; current and voltage), is used to drive the process through available controllable parameters (e.g. burner oxygen and fuel flows; oxygen lancing; carbon injection; and electrode regulation).

The *i* EAF® has been designed considering that there are many variations of the EAF process in the market place. The basic models are applicable regardless of the type of furnace while the differences are taken into account via customized control modules that are tailored to each application. In this way, the *i* EAF® is applicable to any EAF; be it a traditional bucket charged scrap operation, a continuously charged shaft or Consteel® process or a furnace using alternative iron sources such as DRI or hot metal. While the basic structure remains constant, the automation hardware, software and communication modules are customizable according to each customer's existing automation system and network.

Conceptually, the components of the *i* EAF® form a pyramid (as shown in Figure 1) where each layer builds upon the previous to form the *i* EAF®. Specifically, the layers of the *i* EAF® are:

- *i* EAF® Sensors and Instrumentation.
- *i* EAF® Dynamic Process Models.
- *i* EAF® Control and Optimization Modules.

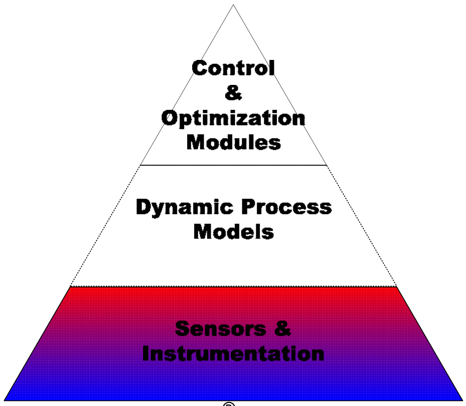

Figure 1: The *i* EAF® conceptual pyramid.

Online sensors and the integrated mathematical models provide fundamental process knowledge that permit advanced control of the EAF process. Process models extend the primary information to provide process information that is used to control the EAF. The details of each of these layers are provided in the following sections:

2 SENSORS AND INSTRUMENTATION

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®; with the EFSOP® off-gas analysis system being a necessary component. 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.
As 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.

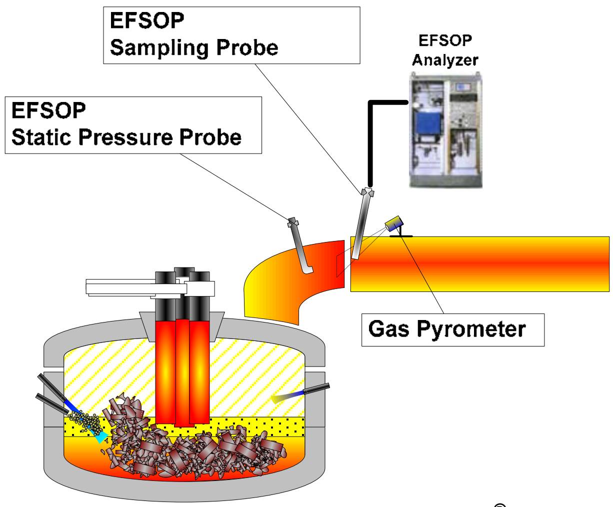

Figure 2: A schematic of the Basic *i* EAF® Sensors

A number of other sensors have been developed or adapted for application to the EAF. These include an infra-red gas pyrometer that measures the temperature of the off-gas as it leaves the primary duct of the EAF and a pressure probe for measuring the static pressure of the gases in the primary duct of the EAF. This probe, designed similarly to the EFSOP® sampling probe has been demonstrated to be much more reliable and requires less maintenance than more commonly found static pressure ports located in the roof of the furnace.

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:

- An optical camera, installed above the furnace for viewing the extent of melting before charging, provides a method for gauging the progress of the heat for multi-charge furnaces.
- A laser based system for determining the height of the liquid heel and slag at the start of the heat.
- Weigh cells, standard on furnaces equipped with Tenova's Consteel, provide a dynamic indication of the furnace weight.
- Continuous flat-bath temperature measurement via pyrometric methods.

At present, the mass rate of gases leaving the EAF are estimated using the static pressure measured in the primary elbow of the furnace. A more accurate determination of off-gas mass rate is possible through the use of a secondary analyzer paired with a traditional flow sensor placed in the furnace off-gas duct, downstream of the combustion gap. A carbon balance between the primary sampling point of the EFSOP® analyzer and the sampling point of the secondary analyzer is used to calculate the ratio of furnace off-gas making up the downstream flow. The rate of gases leaving the EAF is then the product of this ratio and the measured downstream flow rate.

3 DYNAMIC PROCESS MODELS

The *i* EAF® is based on the philosophy that it is possible to determine important dynamic information about the steelmaking process from the measured off-gas composition. Tenova has developed three dynamic process models that work together to describe the EAF process. Each of the three models correspond to one of the three phases found in the EAF:

- The *i* EAF® Freeboard Model that describes the gas-phase.
- The *i* EAF® Bath/Slag Model that describes the liquid phase.
- The *i* EAF® Melting Model that describes the solids phase.

The *i* EAF® Freeboard Model, shown schematically in Figure 3, takes as its inputs: the rate of oxygen and fuel, delivered to the freeboard through the burners and fix-wall injectors and the rate of flow, temperature and composition of the off-gas. Given these inputs, carbon and oxygen mass balances are used to calculate, dynamically, the net rates of the carbon and oxygen reactions; indicated in the figure as the rate of oxidation and the rate of decarburization.

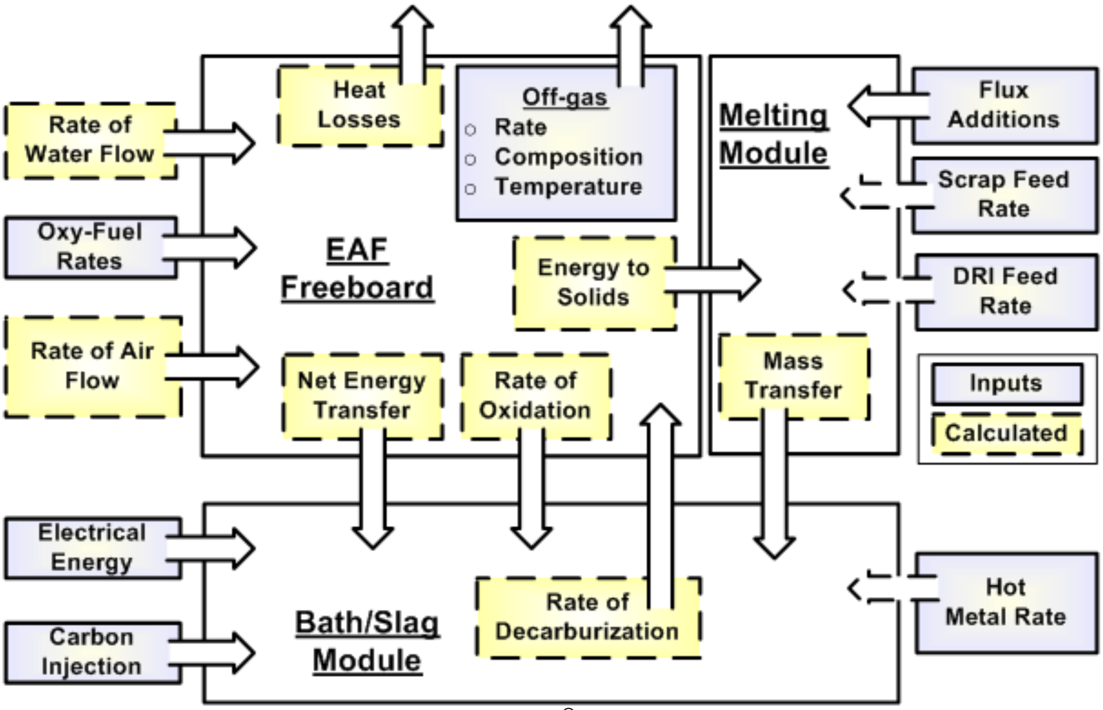

Figure 3: The *i* EAF® Dynamic Models

Although labeled "rate of decarburization", this term accounts for all sources of carbon (excluding methane) entering the freeboard (not only carbon liberated from the steel bath) of the furnace; including: injected or charged carbon; carbon from hydrocarbons entering with the scrap; carbon from electrode wear; as well as carbon reacting with the slag in the reduction of iron oxide.

Similarly, the rate of oxidation term accounts for all sinks for oxygen entering the freeboard; including: oxygen attributed to combustion of charged or injected carbon; oxygen for the combustion of hydrocarbons entering with the scrap; and the oxygen attributed to the oxidation of iron and other metals for slag formation.

The rate of air entering the freeboard of the furnace is calculated using a nitrogen balance while the rate of water entering the freeboard is calculated using a hydrogen balance. The "rate of water in-leakage" accounts for all sources of water including: the rate of water entering the freeboard from the electrode cooling spray; the products of combustion of hydrocarbons entering with the scrap; water or snow entering with the scrap; and water from leaks in the water-cooled panels and other water-cooled circuitry encompassing the furnace.

Another component of the *i* EAF® freeboard model is an energy balance. The inputs and the material balances are used to calculate the net energy losses from the freeboard. The net energy is then partitioned between losses from the furnace; energy to heat and/or melt solids (scrap, DRI, fluxes, etc.) and energy transfer between the bath/slag.

The *i* EAF® Dynamic Bath/Slag model is based on the determination of the rates of oxidation, decarburization and energy losses provided by the freeboard mass/energy balance. This information makes it possible to evaluate the bath and slag status (temperature and composition) dynamically and in real-time.

The *i* EAF® Melting model, builds upon the calculations from the freeboard model and the subsequent model of the bath/slag. Given the net energy (both chemical and electrical), the melting model is able to calculate the distribution of energy between heating (increase of scrap temperature) and melting (from solid scrap to liquid steel). In this way, the progress of scrap melting is calculated. The dynamic calculation, in turn, allows the

heat to be paced (more details later) according to the rate of scrap melting and not only on the common electrical energy clock.
The approach taken by TGI differs in a fundamental way from the approach taken by others in that the off-gas composition is not an estimated parameter, used to complete the energy balance of the freeboard; but is instead treated as an input to the models for the direct determination of the dynamics of the process. This approach makes it possible to determine an energy balance that takes into account the variability of the EAF process. This improved accuracy is necessary for effective control and optimization of the EAF process.

4 PACING THE EAF

Typically, the delivery of chemical energy to the EAF is based on fixed profiles defining oxygen, fuel, carbon and lime injection setpoints. These standard profiles are used to determine the working points as a function of the specific electrical energy supplied to the furnace (kWh/t). That is, the furnace is paced according to an electrical energy clock. The same principle is applied to the electrical program and in some cases to control the fume system.
The problem with this strategy is that the rate of electrical energy delivery does not correspond to the rate of progress of the process. The incongruence between heat progress and the electrical energy clock has become more of an issue in recent years where the EAF process has become much more dependent on chemical energy than before. Today, heat progress is a stronger function of total net energy (electrical plus chemical) supplied to the furnace; and not electrical energy alone.
The inefficiencies introduced to the process by pacing the furnace only on electrical energy are explained by Figure 4. The percentage of scrap melted for two hypothetical heats is plotted as a function of specific electrical energy delivered to the furnace.

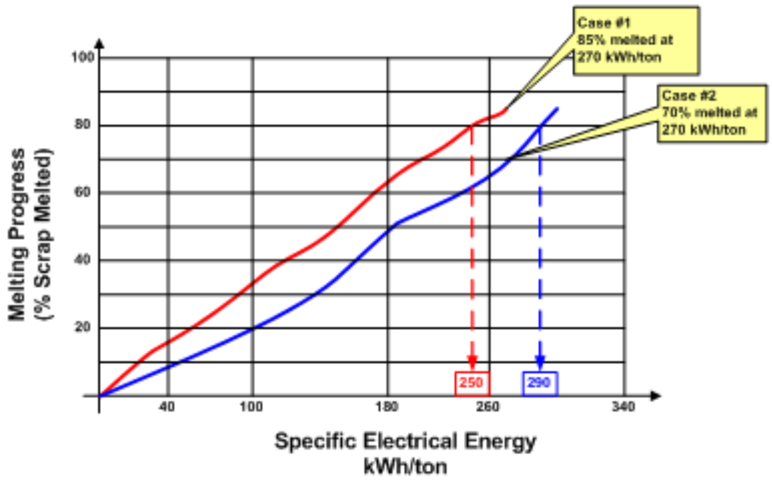

Figure 4: A plot of melting progress as a function of specific electrical energy consumption showing inefficiencies associated with pacing the furnace on specific energy consumption

In the first case, 85% of the scrap is melted using 270kWh/t; while in the second case, 70% has been melted with 270kWh/t electrical energy. Suppose that from an operational point of view, the ideal time to charge is at 80%; as this may be the point when just enough scrap has been melted to allow for the volume of the next charge. The inefficiencies associated with a fixed electrical energy based profile become clear. In the first case, the charge could have been stopped earlier at 250kWh/t; while in the second case, the charge requires that the operator wait until energy input has reached 290kWh/t before charging the furnace. If the operator bases the decision to charge the furnace at the nominal 270kWh/t of electrical energy, he would be too late for the first case and too early for the second.

Similar issues occur with many aspects of the operation. For example: refining start time, stepping of burner set points, start of carbon injection, refining start point, electrical tap settings, fume system damper control, etc. The progress of the heat is a stronger function of percentage melting than it is of specific electrical energy delivery and so, the furnace should be paced accordingly. This particular issue with pacing the EAF has been recognized by others who have also tried to pace the furnace according to total energy delivery. Their success, of course, has been limited by the fact that, without off-gas composition, their models consider only the nominal chemical energy and not the actual chemical energy evolved in the furnace and the real losses to the off-gas.

5 CONTROL, OPTIMIZATION AND SAFETY MODULES

At the top tier of the *i* EAF® pyramid are the control and optimization modules. These modules evaluate the comprehensive information provided by sensors and instrumentation and the process models and determine how to drive the process by suitable control actions conducted in real time. A number of optimization modules have been developed to control and optimize the EAF process; these include:

- Water Detection Module;
- Cost-based post-combustion optimization module;
- Electrical energy optimizer;
- Refining start detection;
- Foamy slag optimizer;
- End-point detection.

Water Detection Module: Of particular interest and benefit to operators is the ability to predict the presence of water in the freeboard of the EAF. Small quantities of water in the off-gas are normal and comes from a variety of sources; including: combustion of methane, combustion of hydrocarbons on the scrap steel; water from cooling of the electrodes, etc. A serious source of water entering the free-board of the EAF results from leaks that develop in the sidewalls and roof of the EAF. These leaks present a serious safety problem in that the leaks may lead to explosions. There are two methods of explosion: a) steam explosions from the mixing of water with molten steel and b) the dissociation of water into hydrogen gas. In the first case, water trapped beneath molten steel will evaporate violently expelling molten steel from the furnace. In the second case, water may dissociate into hydrogen gas resulting in the formation of an explosive mixture of gases that could ignite in the presence of oxygen. Regardless of the mechanism, water in the EAF presents a serious and dangerous situation.

An output of the freeboard mass and energy balance is the rate of water in-leakage into the furnace. The value provided by the model includes water entering the freeboard from all sources excluding the combustion of methane. Statistically, it is possible to separate out the common sources and establish a fingerprint of water in-leakage that is considered normal and acceptable. Deviations from this fingerprint are indicative of a water-leak. The water detection module aims to distinguish normal water entry into the furnace from dangerous water-leaks and alarm accordingly.

Post-Combustion Module: The benefits provided by post-combustion in the EAF have been debated extensively over the past decade. The idea that excess oxygen imparted to the freeboard of the EAF to combust carbon monoxide has been implemented to various degrees of complexity. The simplest implementation has been based on an estimate of the efficiency of post-combustion over the course of the heat. This value is used to determine a necessary amount of excess oxygen. The standard profile for oxygen setpoint settings are then adjusted accordingly. This method requires the use of static burner profiles that are typically designed on an electrical kWh/t clock. The basic EFSOP® approach improved upon the nominal approach by using the off-gas composition to dynamically control excess oxygen in response to measured off-gas composition and the extent of combustion. The methodology uses fixed profiles based on specific electrical energy consumption to control the timing of the burner program but features closed-loop control to adjust the rate of oxygen (and methane).

Whereas the basic EFSOP® approach optimized post-combustion based on the extent of combustion alone, the *i* EAF® post-combustion control module has been designed to control and optimize post-combustion in the EAF based on a balance of the benefits of energy recovery against the costs for methane and oxygen consumption. This is possible through the use of the freeboard mass and energy balance. At each control cycle, the module is able to estimate the heat transfer efficiency of post-combustion in the freeboard and attributes an economic benefit ($/MW) to that energy. At the same time, the costs of oxygen and methane ($/Nm3) are also considered. Maximization of the net benefits provides the optimal setpoints for oxygen and methane. The objective function described above is constrained by the mechanical limitations of the oxygen and methane delivery systems and other operational considerations. As described earlier, a further improvement over the traditional approach is that the burner profile is paced according to melting percent and not kWh/ton.

<u>Electrical Program Optimizer</u>: The electrical program optimizer module works to modulate the electrical working points dynamically over the course of the heat so as to ensure the most efficient transfer of electrical energy to the furnace. The module is based on a model of the electrical behavior of the furnace and has been designed to anticipate and predict the electrical energy transfer to the scrap and bath. The module's control actions are based on the monitoring of current and voltage through the dynamic triangular electrical diagram to detect imbalances. The arc length of each phase is monitored and modulated as a function of the process (e.g. panel temperatures, harmonic levels, oxygen and carbon injection, etc.). The electrical current is regulated as a function of the process stage.

<u>Refining Start Detection</u>: At a point during the final charge, the operation switches from "melting mode" to "refining mode". During the melting phase, the burners are used to heat and melt scrap. After the transition to refining, the burners may be disabled or placed in a low-fire mode. In furnaces equipped with fixed-wall injectors, the injectors are taken from subsonic oxygen flow (burner mode) to supersonic flow (lance mode). Without a clear indication of when to switch from melting to refining mode, operators rely on cues from the process; such as: a fixed kWh/ton value, visual inspection through the slag door, the sound of the furnace, and arc stability. The issues associated with timing the transition from melting to refining based only on specific electrical energy were discussed previously. The transition from melting to refining should be based on the extent of melting.

Ideally, the furnace should transition from melting mode to refining mode when just enough scrap has been melted so that the height of the bath is sufficient for the injectors to operate effectively. The role of the *i* EAF® Refining Start Detection Module is to determine the ideal point to transition to refining. While the 'percentage melt' is the key indicator, other cues from the process are taken into account. Cues from the electrode regulation system top the list; for example the harmonics analysis available from the electrode regulation system (TDR-H), is a strong indicator that flat-bath operation has been reached.

<u>Foamy Slag Optimizer</u>: The EAF slag performs a variety of functions: it insulates the steel bath to reduce heat losses; absorbs the products of oxidation from the steel; covers the electrical arc to facilitate the transfer of electrical energy to the bath; protects the lining and panels on the sides and roof of the furnace and protects the steel bath from

picking up undesirable gases (e.g. nitrogen and hydrogen). For optimum performance, and to ensure proper foamability, it is necessary to maintain the slag at the proper chemical composition and temperature. Deviations from the range of ideal composition and temperature result in a slag that does not foam properly. The bath/slag model evaluates the slag composition dynamically during the refining period. This is possible because the rate of oxygen contributing to oxidation and the rate of decarburization for iron reduction are determined dynamically. Other indicators such as arc stability and electrical harmonics are used to control the foamy slag practice by manipulating oxygen, carbon and lime injection.

End-point Optimizer: Experience teaches that the most efficient way to operate an EAF is to achieve both composition and temperature endpoints at the concurrently at the end of the heat. This module controls the refining period so that carbon and temperature end-points are achieved at the same time. The *i* EAF® End-Point Optimizer Module calculates the expected carbon and temperature trajectories and takes control actions to align the two by increasing/decreasing the oxygen injection rate or by adjusting the electrical working point. Controlling the process so that both carbon and temperature end-points are reached at the same time addresses another commonly encountered inefficiency. If the desired carbon is reached too soon before the temperature end-point the steel bath will most likely be over-oxidized requiring the use of de-oxidants or the re-addition of carbon. Alternatively, if the temperature is reached too soon before the carbon end-point, excessive energy would be required to maintain the higher temperature for longer periods of time.

6 SUMMARY

Scientist and pioneer in thermodynamics, William Thomson, Lord Kelvin (1824-1907), has been quoted as having said: *"When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge of it is of a meager and unsatisfactory kind..."* It follows that one cannot possibly control what one cannot measure. The *i* EAF® has been designed to explain the EAF process as quantitatively as possible by using real-time measurements of furnace off-gas composition and other measurable process parameters. It builds upon this information through process models that quantify the EAF process dynamically and in real-time. Quantification of the process enables precise control of the melting and refining phases of the operation; first of all through pacing of the furnace according to the total energy (not only electrical) delivered to the scrap and steel, and secondly through optimization modules that have been designed to control the furnace in the most efficient manner possible.

TenarisDalmine, located in Dalmine Italy, has agreed to host the premier application of the *i* EAF®. Thanks to the collaborative efforts of TenarisDalmine, Tenova Automation and Tenova Goodfellow the project is well underway; sensors have been installed and the process models have been implemented online. Examples of the SCADA operating screens implemented at TenarisDalmine, are shown in Figure 5. The screens, updated dynamically over the course of the heat, provide the furnace operator with real-time process information provided by the sensors and the models described above.

Figure 5: *i* EAF® SCADA operating displays

The control modules have been developed and are currently being validated and tuned. Once fully implemented, the *i* EAF® will provide a variety of benefits to the steel-maker. During the melting phase, the pacing and control of the chemical package will ensure:

- A reduction in power-on-time.
- A reduction in delays attributed charging the furnace too early.
- A reduction in energy losses attributed to charging the furnace too late.
- Optimization of oxygen, fuel and electrical energy usage.
- Efficient fume system control that is balanced against furnace performance and melt-shop air quality.
- Safety in the melt shop through the early detection of water in the freeboard.

The advanced control modules for refining (Refining Start, Foamy Slag Optimizer, End-Point Optimizer) will ensure:

- Avoiding over-oxidation of the bath and thereby minimizing yield losses and the use of expensive de-oxidants.
- Balancing the foamy slag practice and thereby decreasing refractory wear; decreasing energy losses during refining; and increasing yield through slag losses.
- Reduction in the variability of the end-point and thereby improve overall meltshop logistics.
- Reduction in the number of samples of temperature and carbon required to conclude a heat.

The *i* EAF® provides a deeper understanding of the EAF steelmaking process and operation. The opportunities resulting from this deeper understanding will no doubt contribute greatly towards more efficient operation and to the development of future optimization strategies for the EAF.

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