Tenova's intelligent arc furnace 'iEAF' – Concept and technical overview

The 'intelligent electric arc furnace', trademarked iEAF™ is an innovative automation system, based on continuous, real-time process measurements and online process models, developed for the dynamic control and optimisation of the electric arc furnace (EAF).

By P Clerici*, F Dell'Acqua*,
J Maiolo*, S Vittorio*

BUILDING upon the EFSOP™ real-time off-gas analysis system, the iEAF™ is an extension of Tenova's holistic approach to EAF control and optimisation. The benefits provided by real-time off-gas analysis have been documented extensively over recent years. Historically, steelmakers have relied on static process information and highly simplified models to operate and control their EAF's. The adoption of real-time off-gas analysis has provided many steelmakers with a tool for understanding the dynamics of their process; but the benefits of off-gas analysis do not end there.

At its most basic level, the iEAF provides process models to elucidate, from the profile of off-gas composition, important steel-making information; and thereby provide process engineers with a deeper understanding of their furnace operation. This understanding, in turn, is indispensable for achieving improvements in the process itself. Control actions, based on real-time process information, help the operator to; reduce conversion costs; improve productivity; and address environmental concerns.

EAF shops are equipped with a variety of different automation systems for controlling the EAF such as electrode regulation, chemical energy injection control system, fume-system control, etc. Seldom does one find a unified system to control the EAF and its auxiliary systems. The iEAF is designed for this purpose, to bring together the control and automation of the furnace and auxiliaries under one automation umbrella.

Fig 1 summarises the integrated approach of the iEAF system. As a complete package, the iEAF brings together all aspects of the furnace operation. Feedback from the process, provided by various sensors (eg off-gas analysis; electrical harmonics, current and voltage, etc), is used to drive the process through controllable parameters (eg burner oxygen and fuel flows, oxygen lancing, carbon injection, electrode regulation, etc). Both electrical and chemical energy are taken into account.

The iEAF has been designed around the typical EAF but considering that there are many variations in the market place; for instance a furnace may be either: a top-charged scrap operation, a continuously charged operation (eg Tenova's patented Consteel® process), or furnaces incorporating other continuously charged iron sources (DRI, HBI, hot-metal). Differences are taken into account via control modules that are tailored to the process and in communication modules that implemented according to the customer's control systems and networks.

Fig 2 illustrates the modularity of the iEAF as applied to a meltshop fitted with the full suite of Tenova technologies for the EAF: The EFSOP system for off-gas analysis and chemical energy control and process optimisation; the TDRH for digital electrode regulation; the iMelt® for basic furnace automation and control; and the iLance® system for control of Tenova's KT injection systems. As for implementation, the modularity of the hardware ensures that the installation is not disruptive to the normal operation of the meltshop, and in fact may be implemented during normal operation and by making use of regularly scheduled weekly maintenance outages.

iEAF structure & components

From a process point of view, the components of the iEAF may be grouped into three distinct groups that, as an integrated package, become the Intelligent EAF:

- iEAF system hardware and additional instruments;
- Mathematical process models;
- Control and optimisation modules.

With respect to process control and optimisation, direct information from the process, via sensors and instrumentation, is most desirable. It is also recognised that melt-shops differ in the extent of instrumentation available. The iEAF must be adaptable to function regardless of the level of instrumentation encountered at the plant. Simply, if something is measurable, then it is measured; if not, a process model or 'soft sensor' will be developed to estimate the desired process parameter. The exception to this is the EFSOP off-gas analysis equipment as this is a pre condition for the installation of the iEAF.

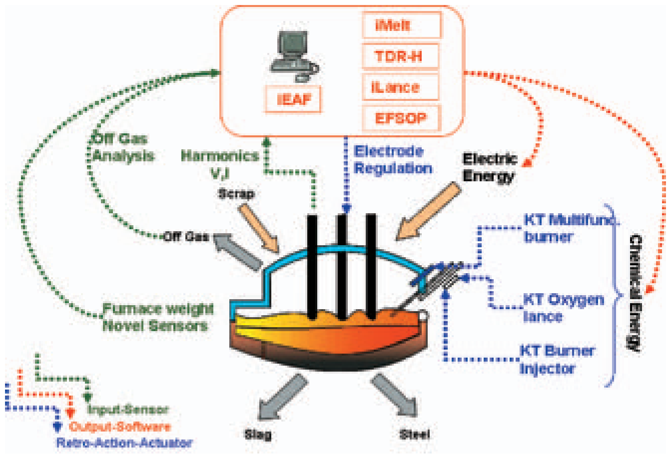
Instrumentation, sensors & hardware

In addition to the EFSOP off-gas analysis system, the iEAF makes use of additional process sensors to gain as much dynamic information about the process as possible, including:

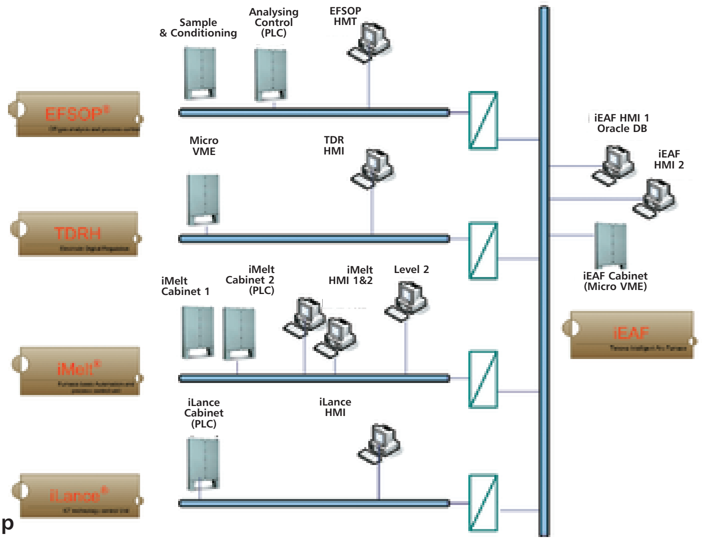
- An infra-red, thermo camera used to measure the temperature of the off-gas at the elbow of the furnace.
- The mass rate of gases leaving the EAF, based on the measurement of static pressure, in the primary elbow of the furnace, and an internal energy balance (Bernoulli's equation) to calculate the flow given the furnace geometry.

Other methods for determining off-gas mass flow are being considered. One solution includes coupling a traditional flow sensor with a secondary analyser located at some point downstream of the furnace. A secondary off-gas analysis enables the accounting of dilution air flow based on a carbon balance between the primary EFSOP measurement point and the downstream analyser.

In addition to the above instrumentation



(fig 1) Integrated approach of the iEAF™ system



(fig 2) (right) Modularity of the iEAF as applied to a meltshop

---

***Authors:** *Tenova Italy, **Tenova Goodfellow, Canada

Equipment		Models		
EFSOP + Additional sensors	**Bath optical sensor**	**Freeboard**	**Melting**	**Bath/Slag**
CO concentration CO_2 concentration H_2 concentration O_2 concentration Fourth hole off-gas temperature Elbow static pressure	Continuous bath temperature	Off-gas flow rate Air ingress flow H_2O ingress flow CO decarburation rate O_2 Oxidation flow Energy to charged material Energy in freeboard Losses to off-gas Losses to panels	Melting percent Onset of flat bath Scrap temperature Liiquid bath temperature	Liquid steel weight Liquid steel composition Slag Weight Slag composition Bath temperature Slag physical properties

(table 1) Measured and calculated parameters for iEAF

and other 'traditional' measured process parameters, there are a number of experimental sensor technologies currently under development by Tenova. 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-charged 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 ConSteel equipped furnaces, to provide a dynamic measure of the furnace weight.
- Continuous flat-bath temperature measurement via pyrometric methods.

Mathematical process models

At the heart of the iEAF package are three dynamic process models that describe the EAF process, each corresponding to one of the three phases found in the EAF:

- Freeboard Model for the gas-phase.
- Melting Model for the solids phase.
- Bath/Slag Model for the liquids phase.

The iEAF Freeboard model, shown schematically in **fig 3** is a dynamic model of the freeboard (gas-phase) of the EAF. The EFSOP system provides real-time measurements of off-gas composition and temperature, and static pressure measured in the primary elbow of the furnace. The process measurements are, in turn, used to close the mass and energy balance of the gas-phase of the process.

Based on this, a complete mass and energy balance allows the estimation of:

- Water entering the freeboard;
- Air in leakage;
- Carbon (as CO);
- Rate of oxidation (slag formation) ;
- Rate of heat flow out of the freeboard.

The approach differs from that typically taken by others, as the method does not consider off-gas composition as a variable to be predicted (or used to tune the steelmaking models) but instead as a direct input into the modelling effort. Furthermore, the predicted rates are, at this point, purposely generic, and not attributed to any specific phenomenon. That is, for example, the water entering the freeboard may come from electrode cooling, the product of combustion of hydrocarbons or some other source of hydrogen; the carbon may be attributed to the combustion of hydrocarbons, electrode consumption, injected carbon, charged carbon, etc.

The freeboard model, executed dynamically over the course of the heat, provides the necessary information of optimal control of the burners, lances and injectors; with an immediate impact in the consumption decrease and realisation of operating practice. Moreover, they provide precious information for the optimal evaluation of the melting progress and for a more precise description of the molten bath and slag, so that furnace control is possible throughout the process.

The iEAF Dynamic Bath/Slag model, as illustrated in **fig 4** is based on the estimates of oxidation, decarburisation and energy losses provided by the freeboard mass/energy balance and is therefore more accurate than before in evaluating the bath and slag status (temperature and composition). Consequently, a real control is possible for foamy slag, decarburisation and overheating in refining or continuous charge.

The iEAF 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, less losses), the melting model is able to calculate, in real-time, 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 melting percent and not only on electrical energy, as is commonly done. The approach lends itself to the application of control modules to optimise the overall process.

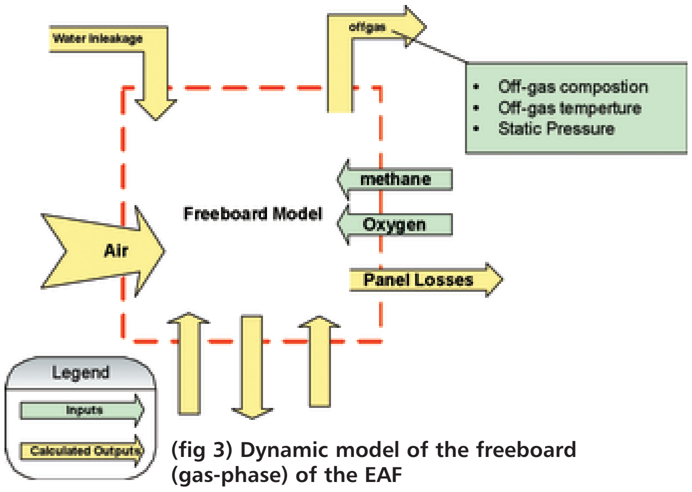
Online sensors and the integrated mathematical models provide fundamental process knowledge that permits advanced control of the EAF process. The information derived from the free-board model, combined with that from the melting and bath/slag models add to the understanding of the melting process.

Table 1 provides a summary of the measured and calculated parameters and gives a summary of the extent of new available information provided by the iEAF.

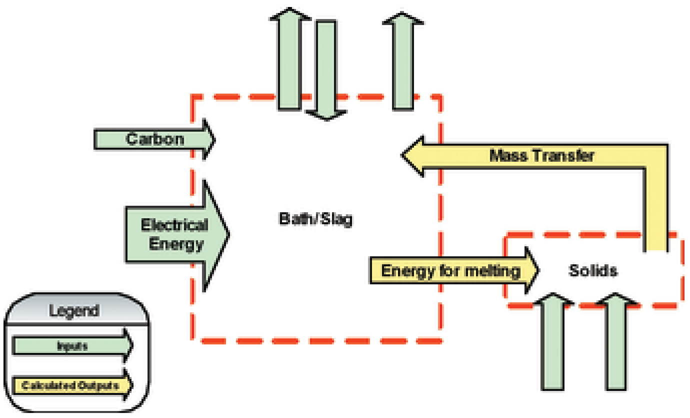
With this additional information, the iEAF is able to perform advanced control of the EAF. The following sections provide the details of the philosophy of the process.

Pacing the EAF

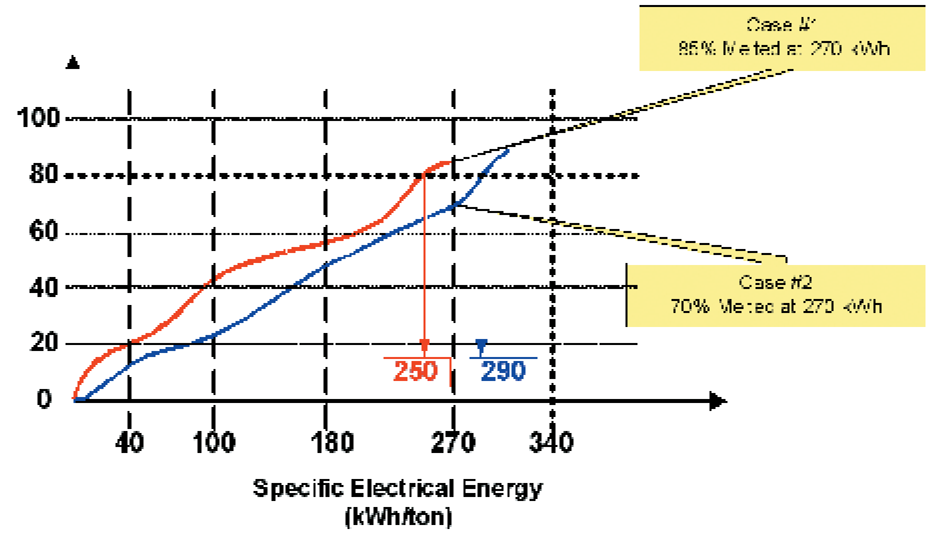
Typically, the delivery of chemical energy to the EAF is based on fixed profiles of oxygen and



(fig 3) Dynamic model of the freeboard (gas-phase) of the EAF



(fig 4) iEAF™ Dynamic Bath/Slag Model



(fig 5) Progress of two hypothetical heats

fuel flow. The standard burner profiles are used to determine the working point as a function of 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 programme and in most cases to the control of the fume system.

The limitations associated with this strategy is that the rate of electrical energy delivery does not necessary correspond to the rate of progress of the process. The incongruence between melting progress and the electrical energy clock becomes more of an issue as an increasing amount of chemical energy is used in the EAF. Common sense leads one to expect that the process is a stronger function of net total energy (electrical and chemical) supplied to the furnace; and not electrical energy alone.

For example, **fig 5** shows the progress of two hypothetical heats, plotted as the percentage of scrap melted as a function of specific electrical energy delivered to the furnace. 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.

Assume further that, from an operational point of view, the ideal time to charge the next charge is at 80% melting; 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 subsequent charge could have been charged earlier at 250kWh/t; while in the second case, the subsequent 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 270kWh/t electrical energy, this would be late for the first case, and too early in the second.

The same 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 recognised 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 do not consider the actual chemical energy evolved in the furnace and the energy losses in the off-gas; as is done by the iEAF. For these reasons, the iEAF uses the percentage melting indicator to pace the furnace, and to define profiles of operation for: the burners, the injectors, electrical energy and the addition of fluxes.

Control & optimisation modules

In addition to the philosophy of pacing the EAF according to a percentage melting clock, the iEAF Control modules evaluate the comprehensive information provided by the Process models and determine how to drive the process by means of suitable control actions, conducted in real-time. A number of optimisation modules have been developed to address the common inefficiencies associated with the EAF process:

- Cost-based post-combustion optimisation;
- Electrical energy optimiser;
- Refining start detection;
- Foamy slag optimiser;
- End-point detection.

Cost-based post combustion optimisation

The idea of, and the benefits provided by post-combustion in the EAF have been debated extensively over the past decade. The idea has been implemented to various degrees of complexity. The simplest implementation starts with an estimate of the efficiency of post-combustion over the course of the heat and adjusts the delivery of super-stoichiometric oxygen accordingly through fixed burner profile settings. This method requires the use of static burner profiles that are typically designed on a electrical kWh/t clock. The traditional EFSOP approach, given the availability of off-gas composition measurements, takes the idea further by dynamically controlling oxygen and methane in response to off-gas composition. The set-points of oxygen and methane flow are adjusted dynamically over the course of the heat, according to a parameter indicative of the extent of combustion.

The iEAF approach builds upon this approach but differs in two main aspects:

- The burner profiles are no longer timed according to an electrical energy clock; but instead paced according to melting percent, resulting in a more consistent operation.
- Instead of controlling oxygen and methane injection, based only on the extent of combustion, the iEAF controls according to an objective function based on the economics of energy delivery to the furnace. This is made possible by the availability of the dynamic mass and energy balance provided by the freeboard model. At each control cycle, the system evaluates the efficiency of chemical energy transfer to the steel and attributes an economical benefit ($/MW) to that energy. At the same time, the costs of oxygen and methane ($/Nm3) are also considered. The maximisation of the benefits less the costs provides the optimal set-points. Successful implementation requires the consideration of mechanical limitations on the oxygen and methane delivery systems and other operational considerations; these are implemented as constraints on the oxygen and methane set point ranges.

Electrical optimiser

The ultimate goal of the Electrical optimiser module is to adjust/correct and adapt the electrical working points dynamically over the course of the heat to ensure the efficient transfer of electrical energy to the furnace. The module is based on a model that represents the electrical behaviour of the furnace. The model has been designed to anticipate and predict the electrical energy transfer to the bath and thereby enhance the operation of the regulation system in response to changes in the process.

Specific objectives of the module include:

- Optimise the electrical working point, based on the dynamic circular diagram;
- Dynamic regulation of the electrical current, as a function of the process stage;
- Smart evaluation of the operation of the regulator for melting and refining stages.

Electrical optimisation is accomplished by dedicated control actions; for example: the automatic detection of unbalances of current and voltage as a function of the Dynamic Triangular Diagram and its recovery; the monitoring, for each phase, of the arc length and its modification as a function of the process variables (panel temperatures, harmonic levels, oxygen and carbon injection) with the ultimate goal of optimising energy transfer (both electrical and chemical).

Refining beginning detector

The aim of this module is to provide a consistent point in the heat for the start of the refining operations (oxygen lancing, carbon injection, lime injection). As is typical, in the melting phase the burners and oxygen injectors are used to heat and melt scrap; while in refining, the burners are disabled or reduced to low-fire mode and oxygen injectors are switched to lancing mode. Without a clear indication of when to switch between these two differing modes of operation, operators rely on cues from the process (eg visual inspection through the open slag door, the sound of the furnace, arc stability, achievement of a certain kWh/t electrical energy consumption, etc). The issues with timing the transition from melting to refining based on a kWh/t electrical energy

Controller Controlled equipment	Chemical programme	Electrical programme	Materials charge programme	Electrical optimiser	Refining beginning detector	Foamy slag optimier	End point optimiser
Electrodes Regulation		●		●	●		●
Lime injectors	●				●	●	
Carbon injectors	●				●	●	●
5th hole additives and fluxes			●			●	
Burners	●						
KT lances as burners	●						

(table 2) Summary of the control modules and where their actions are directed.

clock has been discussed earlier. From the point of view of the process, the transition should be based on what is physically happening in the furnace and that is the achievement of flat bath (a sufficient amount of scrap has been melted) and the stabilisation of the arc. With the iEAF it becomes possible to automatically detect flat-bath conditions and hence determine accurately the start of refining. While the 'percentage melt' is the key indicator, other cues from the process are taken into account, for example the harmonics analysis available from the electrode regulation system (TDR-H).

Furthermore, switching from melting mode of operation to refining mode does not necessarily have to be a discrete event for all injectors/burners at the same time. There are also opportunities to switch part of the chemical package to refining while maintaining others in melting mode.

Foamy slag optimiser

The electric furnace slag performs a variety of functions: insulates the steel bath to reduce heat losses; absorbs the products of oxidation from the steel (FeO, Al_2O_3, SiO_2, P_2O_5, etc); covers the electrical arc to facilitate the transfer of electrical energy to the bath and protects the lining or the panels on the furnace sides and roof; and protects the steel bath from picking up undesired gases such as hydrogen and nitrogen.

For optimum performance, and to ensure a foamy slag practice, it is necessary to maintain the slag at the proper chemical composition and temperature. Deviations from an ideal composition and temperature could result in a slag that does not foam properly. Factors that can be manipulated for the maintenance of a proper foamy slag include oxygen injection (formation of iron oxide) and carbon injection (reduction of iron oxide). Also in some plants, the addition of lime or dolomite is possible during the refining stages through lancing or roof-loading.

The bath/slag model, permit the evaluation of slag composition dynamically over the course of the refining period. This is possible because the oxygen contributing for slag formation is calculated dynamically. The reduction of iron oxide, by carbon injection or decarburisation reactions, is also calculated. These, along with indicators such as arc stability and electrical harmonics are used to control the foamy slag practice dynamically.

End point optimiser

Experience teaches that the most efficient way to operate an EAF is to achieve both composition and temperature endpoints at the same time at the end of the heat. The aim of this module is to control the refining period so that carbon and temperature end-points are achieved congruently. The end-point predictor model, calculates the expected carbon and temperature trajectories. Control actions are taken to align the two (for example by increasing or decreasing oxygen injection, or possibly by adjusting the electrical working point.

Control modules coordination

Generally speaking, all of the modules have been designed to operate as continuously as possible over the course of the heat (**Table 2**). As such, conflicting decisions could arise from the individual control modules. To avoid this, the following general rules are implemented:

- Set points, defined by the Chemical Programme and Electrical Programme may be changed/overwritten (inside certain ranges) by the other modules.
- Material Charge Programme defines charge operations that are executed at the correct time. Possible conflicts are avoided by the Foamy Slag Optimiser considering the operations scheduled by the Material Charge Programme before defining its actions.
- Post Combustion Optimiser operates in the melting phase only and is a secondary consideration during refining.
- The Foamy Slag Optimiser and the End Point Optimiser work during the refining phase only. The control actions coming from each can potentially conflict. To avoid this, one is given priority over the other according to operations considerations.

Savings and benefits

The great scientist and a father of thermodynamics, William Thomson, Lord Kelvin (1824-1907), has been quoted as saying:

"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..."

Moreover, one cannot possibly control what one cannot measure. The iEAF is based on this sentiment in that it has been designed to explain the EAF process as quantitatively as possible.

Precise control of the melting phases, through; pacing of the furnace according to total net energy and cost-based post-combustion, ensures:

- Reduction in power-on-time;
- Reduction in delays attributed to charging (power-off delays between charges);
- Optimisation of consumables (oxygen, fuel and electrical);
- Efficient fume system control balanced against furnace performance.

During the refining stage, the advanced control modules, including the start of refining, the foamy slag optimiser and the end-point optimiser, ensure:

- Minimising over-oxidation of the bath (therby minimising ferro-alloy additions);
- Balancing the foamy slag practice (decreased refractory wear, increased yield through minimising slag mass);
- Increased yeild;
- Reduction in variability at end-point and overall meltshop logistical benefits;
- Reduction in the number of samples of temperature and carbon required to conclude a heat.

In addition to these benefits, there are many others, that although not as easily quantifiable, they do, nonetheless, provide the steelmaker with enormous benefits:

- Increased safety from the detection of unusually high or abnormal concentrations of water in the furnace off-gas (attributable to water leaks);
- A deeper understanding of the EAF process and operation;
- The opportunities resulting from a deeper understanding of the process, to evaluate trials and develop strategies for improved operation.

The iEAF system is not only modular, but may be considered to be an 'add-on' and it is therefore perfectly integrable with existing process automation systems.

TenarisDalmine has agreed to host the premier application of the iEAF. Thanks to the collaborative efforts of (TenarisDalmine, Tenova Automation, Tenova Goodfellow), the project is well underway. The process models have been programmed and are being tuned and validated to Dalmine's operation. ■

References

1. J Maiolo, E J Evenson, O I Negru, 'Goodfellow EFSOP® Successes at TAMSA, Veracruz', AISTech 2004 Conference, Nashville, TN, September 2004

2. J Kelleher, M I Khan, 'Yield and Productivity Savings Using Goodfellow EFSOP® at MacSteel Arkansas', AISTech 2006 Conference, Cleveland, OH, May 2006

3. D Vensel, M I Khan, 'EAF Performance Improvement at Nucor Steel Auburn using Goodfellow EFSOP®', AISTech 2006 Conference, Cleveland, OH, May 2006

4. K Nikkanen, M I Khan, M I , J Gaviña, 'Furnace Water Leak Detection and Reduced Costs Efforts at Aceria Compacta de Bizkaia, Spain using the Goodfellow EFSOP® System,' AISTech 2007, Indianapolis, IN, May 7-10, 2007

5. Maiolo, J A , Boutazakhti, M , Li, C W , Williams, C , 'Developments towards an Intelligent Electric Arc Furnace at CMC Texas using Goodfellow EFSOP® Technology,' AISTech 2007, Indianapolis, IN, May 7-10, 2007

6. 'Operating Results of Goodfellow EFSOP® at Riva, Verona, Italy', M Pozzi, J Maiolo (Tenova Goodfellow Inc), D Masoero, V Scipolo (Tenova S p A) and N Veneri (Riva Acciaio S p A), METEC 2007, Dusseldorf Germany, June 2007

7. 'Optimization of the EAF process at CAPE GATE (PTY) LTD (Davsteel Division) using Goodfellow EFSOP® Technology', V Scipolo, M Khan, S Patil (Tenova Goodfellow Inc) and G Holmes (Cape Gate (PTY) Ltd) to be published European Electric Furnace Conference, Karkow Poland, 2008

Contact

Tenova SpA, Via Monte Rosa 93, I-20149, Milano, Italy
Tel +39 02 43841 Fax +39 02 4384 7695
e-mail metalmaking.sales@it.tenovagroup.com
web www.tenovagroup.com