iEAF® technology: dynamic process control for the electric arc furnace

Tenova’s iEAF® is an innovative automation system for the dynamic control and optimisation of the electric arc furnace that can be tailored to the specific operational objectives of the melt shop. Mathematical models are used along with real-time process information to calculate dynamic mass and energy balances. These provide the operator with crucial steelmaking information such as the net energy to the metallic charge, scrap melting percent, bath and slag composition and temperature. Advanced process control modules use the information to optimise the process through closed-loop control to control and pace the EAF according to the total energy input.

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CONCEPT AND TECHNICAL OVERVIEW

The intelligent electric arc furnace (iEAF®) is an innovative automation system developed for the dynamic control and optimisation of the EAF that is based on the real-time measurement of furnace off-gas composition, dynamic process inputs and online process models. It embodies Tenova’s holistic approach to EAF control and optimisation that builds on the EFSOP® real-time off-gas analysis system.

The benefits of furnace control and optimisation based on off-gas measurement using the EFSOP® system have been reported extensively (1-7). Without off-gas analysis, operators have to rely on static process information and highly simplified process models to operate and control their EAFs. 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 provided by off-gas analysis do not end there.

iEAF® 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 rates of oxidation and decarburisation. These direct calculations are then 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 process, 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 iEAF® is designed to bring together the control and automation of the furnace. Feedback from the process, provided by various sensors (eg, off-gas analysis, electrical harmonics, and current and voltage), is used to drive the process through available controllable parameters (eg, burner oxygen and fuel flows, oxygen lancing, carbon injection and electrode regulation).

As there are many variations of the EAF process in the marketplace, eg, traditional bucket-charged scrap, continuously charged shaft, Consteel® and DRI-based or hot metal-based, the models have been designed to be applicable regardless of the type of furnace; while the differences are taken into account via customised control modules that are tailored to each application. While the basic structure remains constant, the automation hardware, software and communication modules are customisable according to each customer’s existing automation system and network.

Conceptually, the components form a pyramid where each layer builds on the previous to form the iEAF® (see Figure 1). Online sensors and the integrated mathematical models provide fundamental process knowledge that permit advanced control of the 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.

**SENSORS AND INSTRUMENTATION**

Automation and control of the EAF is limited by the many challenges associated with implementing reliable, low-maintenance process sensors in the harsh environment. At the base of the iEAF® pyramid are the sensors and instrumentation; 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® analyser for sampling, conditioning and analysing the furnace off-gas. As shown in Figure 2 the 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 analysed on a dry basis for CO, CO₂, H₂ and O₂.

A number of other sensors have been developed or adapted for application to the EAF. These include an infrared pyrometer that measures the temperature of the off-gas as it leaves the primary duct and a pressure probe for measuring the static pressure of the gases in the primary duct. This probe, designed in a similar way 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 currently in development that could potentially become part of the iEAF® package. These include:

- A laser-based system to detect continuously the electrode position. These measures are used either for diagnostic purposes or to improve regulation performance.
- 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, to provide a dynamic indication of the furnace weight.
- Continuous flat-bath temperature measurement via pyrometry.

The mass flow 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 analyser 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® analyser and the sampling point of the secondary analyser 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.

**DYNAMIC PROCESS MODELS**

Tenova has developed three dynamic process models that work together to describe the EAF process. Each model corresponds to one of the three phases found in the EAF:

**Freeboard model** This describes the gas phase (see Figure 3) and takes as its inputs the rate of oxygen and fuel delivered to the freeboard through the burners and fixed-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 decarburisation.

Although labelled 'rate of decarburisation', 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 and 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 is calculated using a nitrogen balance while the rate of water entering is calculated using a hydrogen balance. The rate of water in-leakage accounts for all sources of water including that 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 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.

**Bath/slag model** This describes the liquid phase and is based on the determination of the rates of oxidation, decarburisation 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.

**Melting model** This describes the solids phase and builds on the calculations from the other two models. 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 (see later) according to the rate of scrap melting and not only on the common electrical energy clock.

The approach taken by Tenova Goodfellow Inc. differs in a fundamental way from others in that the off-gas composition is not an estimated parameter, used to complete the energy balance of the freeboard, but is 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 optimisation of the process.

**PACING THE EAF**

Typically, the delivery of chemical energy to the EAF is based on fixed profiles defining oxygen, fuel, carbon and lime injection set-points. These profiles are used to determine the working points as a function of the specific electrical energy supplied to the furnace (kWh/t), i.e., the furnace is paced according to an electrical energy clock. The same principle is applied to the electrical programme and in some cases to control the fume system.

An issue with this strategy from the operational point
of view 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 increasingly dependent on chemical energy. 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, which is a plot of melting progress as a function of specific electrical energy consumption. The percentage of scrap melted for two hypothetical heats is plotted as a function of specific electrical energy delivered to the furnace. In the first case, 85% of the scrap has been melted at 270 kWh/t of electrical energy, while in the second case, only 70% has been melted. 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 250 kWh/t, while in the second case the charge requires that the operator wait until energy input has reached 290 kWh/t before charging the furnace. If the operator bases the decision to charge the furnace at the nominal 270 kWh/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 point, stepping of burner set points, start of carbon injection, refining start point, electrical tap settings and fume system damper control. 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 specific electrical energy consumption to control the rate of oxygen (and methane). The standard profile for oxygen set-points 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 EFSQP® approach improved on 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 programme but features closed-loop control to adjust the rate of oxygen (and methane).

**CONTROL, OPTIMISATION AND SAFETY MODULES**

At the top tier of Figure 1 are the control and optimisation modules. These evaluate the information provided by sensors, instrumentation and the process models and determine how to drive the process by suitable control actions conducted in real time. A number of optimisation modules have been developed to control and optimise the EAF process. These include:

- Water detection
- Electrical energy optimiser
- Refining start detection
- Foamy slag optimiser
- 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 typical and result from a variety of sources including combustion of methane, combustion of hydrocarbons on the scrap steel and water from cooling of the electrodes. A serious source of water entering the freeboard of the EAF results from leaks that develop in the furnace sidewalls and roof. These leaks present a serious safety problem in that they may lead to explosions. There are two methods of explosion: a) steam explosions from the mixing of water with molten steel leading to expelling molten steel from the furnace, and b) the dissociation of water into hydrogen gas resulting in the formation of an explosive mixture of gases that could explode in the presence of oxygen. Regardless of the mechanism, water in the EAF presents a serious and dangerous situation.

One output of the freeboard mass and energy balance is the rate of water 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 of post-combustion in the EAF have been debated extensively over the past decade. The idea that excess oxygen is imparted to the freeboard 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 set-points 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 EFSQP® approach improved on 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 programme but features closed-loop control to adjust the rate of oxygen (and methane).
<table>
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<th>Melt shop #1 chemical control only</th>
<th>Melt shop #2 chemical and electrical control, one months data</th>
<th>Melt shop #3 chemical and electrical control, one months data</th>
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Table 1 Comparison of results for iEAF® installations (% difference from established baseline)

Improving on the basic EFSOP® approach, the post-combustion control module has been designed to control and optimise post-combustion 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. Maximisation of the net benefits provides the optimal set-points 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/t.

**Electrical energy optimiser** This 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 behaviour 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 (panel temperatures, harmonic levels, oxygen and carbon injection, etc). The electrical current is regulated as a function of the process stage.

**Refining start detection** 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/t 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. As indicated earlier, 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 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.

**Foamy slag optimiser** 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 (eg, 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 as deviations from the ideal range 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 decarburisation 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 optimiser** The most efficient way to operate an EAF is to achieve both composition and temperature endpoints 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. It 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-oxidised, requiring the use of deoxidants 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.

RESULTS FROM iEAF® INSTALLATIONS

The first installation in 2008 at TenarisDalmine, Italy was for research and development purposes (8). Following the installation of sensors and development of the process models and control algorithms, control of the oxy-fuel burner package using iEAF® was tested. The control algorithm for the combustion package was developed to parallel the existing oxygen and methane set points of the plant, but changes the time at which those set points are achieved by using total net energy rather than kWh/t charged or total kWh. Results from these tests are presented in Table 1 as melt shop #1. In 2010, the second installation was completed at a melt shop in Italy with two EAFs. Results from the first month of operation are also presented in Table 1 as melt shop #2. For melt shop #2, the control algorithms were expanded to include electrical regulation as well as the chemical package, and again were developed to parallel the existing set points, but changing the time based on total net energy. These initial results show the potential for a fully optimised furnace with respect to electrical consumption when the chemical and electrical control algorithms are dependent on total net energy.

Examples of the SCADA operating screens implemented 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.

The iEAF® process models have been implemented and are being tuned to the plant’s operation. The off-gas composition for a typical heat is shown in Figure 6. The EFSOP® off-gas analysis system does not measure water.
directly but is determined mathematically, based on the assumption of chemical equilibrium. The water concentration trends according to expectations. During melting it is noted that water concentration is 15-30%, while during refining, it is around 5%. The higher levels are most likely due to the evaporation of water entering with the scrap and electrode cooling sprays and the combustion of hydrocarbons, while the lower levels during refining are due only to evaporation of water from the electrode cooling spray.

Based on the off-gas profile, the iEAF® calculates a mass and energy balance of the furnace freeboard dynamically and in real-time. A balance on hydrogen and nitrogen make it possible to calculate the rate of water and air entering the freeboard volume. The result for this same heat is presented in Figure 7. The relatively high values of water in-leakage at the start of the second charge (~600s into the heat) correspond to the increased water concentration in the off-gas during this period.

With respect to the bath/slag reactions, the freeboard model provides a dynamic indication of the rates of oxidation and decarburisation in real time. Figure 8 is the calculated profile for the same typical heat comparing the rates of oxidation and decarburisation to the rate of oxygen injection. During the first charge, approximately 70 moles/s of oxygen is supplied to the furnace through the oxygen injectors. The figure shows that 50 moles/s of O₂ can be attributed to the oxidation of iron (and other metallics) while the remaining 20 moles/s are attributed to the combustion of charged carbon and hydrocarbons. In comparison, at the start of refining (~1,200s into the heat) oxygen is being supplied at a rate of 40 moles/s. The supplied oxygen, along with oxygen from air entering the freeboard, generates iron oxide at a rate of 55 moles/s equivalent oxygen. Of this total oxygen entering the bath/slag about 45 moles/s returns to the freeboard as carbon monoxide (90 mole/s CO) indicating that iron oxide is being generated at about 10 (55-45=10) moles/s.

During the later stages of refining, the rate of oxidation is approximately equal to the rate of oxygen injection (80 moles/s). During this same period, there are 140 moles/s (70 moles/s equivalent O₂) of CO being generated giving an indication of the rate of slag reduction by injected carbon. This analysis demonstrates how the iEAF® is able to leverage the measurement of off-gas composition and temperature to quantify important steel-making parameters like oxidation and decarburisation.

Extending the mass balance of the freeboard model to the bath/slag makes it possible to calculate (via the bath/slag module) the composition of the slag over the course of the heat as shown in Figure 9. In future this information will be used together with iso-solubility (ISD) diagrams of the slag to provide an indication, in real-time, of the foamlability of the slag. This information, in turn, will form
the basis for control decisions on the injection of carbon or lime for optimum slag foaming.

The freeboard module also calculates an energy balance dynamically in real time. The profile for the same typical heat is presented in Figure 10 where the energy available for heating and melting is compared to the rate of electrical energy input to the furnace. The available energy is the total energy supplied (chemical plus electrical) less the losses to the cooling panels and sensible energy leaving the EAF with the off-gas. As indicated, during the melting period of the first charge, the energy available is greater than the rate of electrical energy supplied by about 5MW, showing the benefits of post-combustion in the freeboard. Alternatively, during refining, the available power starts off at about 10MW less than the electrical input and increases to where they are equal at about 1,700s into the heat. From there, the available energy starts to decrease. In general, during this period the available power to the steel is less than the supplied electrical energy, indicating opportunities for EAF optimisation by minimisation of these losses.

Another feature provided by the bath/slag module is the dynamic calculation of the bath temperature and carbon in real time. The results of this calculation are presented in Figure 11. This calculation forms the basis for the end-point optimiser. The intent is to gauge the trajectories of the carbon and temperature profiles and make process adjustments to ensure that both carbon and temperature are achieved at the same time, thereby addressing the inefficiencies associated with EAF end-point determination.

The predicted temperatures have been compared to the actual measured temperatures at tapping for 100 consecutive heats (see Figure 12). The bath/slag model makes a reasonable determination of the tap temperature and trends well from one heat to the next. Of the 100 heats investigated only one outlier was noted where the error in the predicted temperature was greater than 20°C.

**SUMMARY AND FUTURE WORK**
The iEAF® dynamic process models have been implemented at melt shop #1 and efforts continue toward validation of the results, with the goal of implementing complete dynamic control of both the chemical and electrical set points.

At melt shop #2, work continues on validation of the control modules for the electrical and chemical packages. While the results reported in Table 1 were from one month of operation, the subsequent months have shown significant consumption reductions in electrical energy, oxygen and methane. Once the remaining control, optimisation and safety modules are fully implemented, the iEAF® will provide a variety of additional benefits including greater EAF operational efficiency, fewer losses, reduced consumables and greater plant safety.

![Fig 9 Calculated profile of slag composition](image)

![Fig 10 Comparison of the total available power and electrical power](image)
Work has also begun on installations in Mexico, Canada and Italy. With each installation more development and understanding of the process and control models is achieved due to different operating parameters and equipment that exist at the different melt shops. Also, determining the differences in off-gas flow, the associated energy losses and fume system operations will be a major step toward control and optimisation.

One of the key changes with new installations will be the continued development of measuring off-gas dynamics with the testing of a novel sensor for off-gas flow. This will provide direct off-gas flow measurements from the 4th hole location rather than using pressure and other thermodynamic and fluid dynamic sensors to characterise the off-gas flow.

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