iSteel®: a new approach to reduce steelmaking costs and environmental impact

The impressive results obtained with the EFSOP system have inspired Tenova to expand the utility of real-time off-gas analysis by developing the concept of intelligent steelmaking (iSteel®). It is applicable both to EAF and BOF steelmaking real-time off-gas analysis systems. The approach uses process models to determine, using information from the available sensors (primarily off-gas composition and temperature), important steelmaking information such as the rates of oxidation and decarburisation. These direct calculations are used to dynamically model the bath and slag.

Tenova subscribes to the generally accepted philosophy that real-time dynamic control of the steelmaking process is key for achieving the best overall performance from both the EAF and the BOF. In this regard, the first step towards dynamic process control has been the development of the Goodfellow EFSOP® system for the real-time measurement of furnace off-gas composition and its use in the optimisation of chemical energy use in the EAF. This innovative technology has a very attractive payback based on energy savings, increased productivity, improvements in energy efficiency and environmental benefits. To date, 58 systems have been installed worldwide.

The impressive results obtained with this system have inspired Tenova to expand the utility of real-time off-gas analysis by developing the concept of intelligent steelmaking (iSteel®), which is applicable in a number of areas as shown in Figure 1.

iEAF® and iBOF® are described below; iRecovery is described in the article on page 51.

THE EFSOP® SYSTEM

A key factor is EFSOP, and Figure 2 is a schematic which illustrates the main components of the technology:

Tenova’s optimisation methodology is based on using real-time furnace off-gas composition, along with other process parameters to:

- Identify periods of high carbon monoxide and hydrogen concentrations and/or periods of excessive and possibly inefficient combustion inside the furnace atmosphere
- Assess the efficiency of chemical energy utilisation in the furnace and identify the potential for process improvement

- Evaluate carbon and oxygen balances
- Evaluate the risk of explosion in the off-gas handling system to ensure that the combustion air supply meets process requirements
- Identify excessively over- or under-drafted situations and make adjustments to the fume extraction system as necessary
- Implement the dynamic control of oxygen and methane delivery in response to real-time off-gas composition measurements to ensure efficient combustion within the EAF freeboard

iEAF®

The intelligent electric arc furnace (iEAF®) is an innovative automation system developed for dynamic control and optimisation that is based on the real-time measurement of furnace off-gas composition, dynamic process inputs...
and automation of the furnace and auxiliaries under one automation system and thereby brings together all aspects of furnace operation. Feedback from the process, provided by various sensors (e.g., 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 iEAF® has been designed in the knowledge that there are many variations of the EAF process in use, namely traditional bucket-charged scrap, a continuously charged shaft furnace or Consteel® process, or a furnace using alternative iron sources such as DRI or hot metal. The basic models are applicable regardless of the type of furnace while the differences are taken into account via customised control modules tailored to each application. While the basic structure remains similar, the automation hardware, software and communication modules are customisable according to each customer’s existing automation system and network.

Conceptually, the components of the iEAF® form a pyramid as shown in Figure 3 where each layer builds on the previous one to form the iEAF®. Specifically, the three layers are:

- Sensors and instrumentation
- Dynamic process models
- Control and optimisation modules

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 pyramid are the sensors and instrumentation that form the foundation of the iEAF®; with EFSOP® off-gas analysis system being a necessary component. In addition, a number of other sensors have been developed or adapted for application to the EAF to improve the accuracy of the mass and energy balances that form the basis of the iEAF®. These include an infrared gas 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 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.

The mass rate of gases leaving the EAF are estimated through the use of a secondary analyser paired with a tribo-electric or other more 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** The iEAF® is based on the philosophy that it is possible to determine important dynamic information about the steelmaking process from the measured off-gas composition and other measurable process parameters. To this end Tenova has developed three dynamic process models that work together to describe the EAF process. Each of the three models corresponds to one of the three phases found in the EAF:

- The freeboard model that describes the gas phase
- The bath/slag model that describes the liquid phase
- The melting model that describes the solid phases

One example of use is 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 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.

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 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. This particular issue with pacing the EAF has been recognised by others who have tried to pace the furnace according to total energy delivery. Their success has been limited by the fact that without off-gas composition their models consider only the nominal, and not the actual, chemical energy evolved in the furnace and the real losses to the off-gas.

**Control, optimisation and safety modules** A number of optimisation modules have been developed to control and optimise the EAF process. These include:

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

To date, three installations have been in operation since 2009 in two different meltshops, and another four installations are underway in Mexico, Canada and Italy. With each installation, further 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, since one of the primary results is the characterisation of off-gas flow determining the differences in and the associated energy losses associated with different melt shops and different fume system operations, this is a major step toward control and optimisation.

**iBOF®**

iBOF® is a breakthrough technology designed to reduce greenhouse gas emissions while improving yield, productivity, scrap-melting capability and reducing operating costs. iBOF® technology delivers unprecedented value and an unparalleled level of customised control by employing a combination of reliable off-gas analysis, novel...
sensors and process models linked by a comprehensive automation system. The technology is a modular solution available as a unified package or as standalone systems designed to meet specific customer needs. The technology comprises four principle modules (see Figure 4).

Modules 1 and 3 are based on key sensors and comprehensive process models to predict slag and bath composition and temperature from start to end of blow.

Module 1: End-point detection

This provides improved end-point detection to reduce conversion costs, improve yield and increase productivity, without costly sub-lance technology.

The technology is based on industry-proven EFSOP® off-gas analysis, proprietary off-gas sensors to measure temperature, flow and pressure, and BOF process control models that enable ‘blow & tap’ practice without the additional cost and delays associated with sub-lance technology. In addition, process models also predict slag and bath composition and temperature in real time over the course of the blow and are used to alert operators when to make an in-blow test using their Celox equipment. Subsequently, the system alerts operators when to stop blow based on aim carbon and temperature.

Module 2: Intelligent slopping detection system (ISDS)

This technology uses lance vibration analysis with real-time alerts to give operators advanced warning of the possible onset of a slop and a measurement of slop severity. Early warning enables mitigation of slopping by taking corrective action, for example, through altering lance position and oxygen flow rate, ultimately leading to increased productivity and yield.

Module 3: Optimised post-combustion iBOF®

post-combustion uses EFSOP® off-gas analysis together with temperature, flow and pressure sensors and a dual-flow lance with independent control of primary and secondary oxygen to control secondary oxygen flow-rate, lance penetration and timing. The result is optimal post-combustion efficiency and scrap-melting capability with minimal refractory and lance wear. With typical BOF blowing practice, 85-90% of gas exiting the converter remains as uncombusted CO. This CO represents a significant amount of process energy, since full combustion of C to CO₂ generates 3.5 times more heat than partial combustion to CO.

Controlled injection of secondary O₂ above the lance tip promotes in-converter combustion of CO to CO₂, providing additional energy for higher productivity from increased scrap melting.
Module 4: Automatic tapping control This technology employs advanced image analysis together with process models to control tapping practice, in either operator-assist or fully automatic modes so as to improve safety and minimise slag carry-over and tap alloy additions.

Typical results Results related to the application of modules 1 and 2 in a number of melt shops in North America and Europe are shown in Tables 1-4. Table 1 demonstrates reduced state of bath oxidation and reduced variation.

With reference to Table 2, ‘catch carbon’ is a practice where the steel maker ends the heat blow cycle at carbon content very close to the required final grade carbon content. A typical catch carbon practice is when tapping carbon content of the steel is greater than 0.08%. This allows the steelmaker to reduce the requirement of the secondary metallurgical additions and reduce the overall conversation cost. However, without an accurate prediction, such as one provided by iBOF, there is a possibility of re-blows which introduce delays and can increase the conversion cost.

Prediction accuracy is illustrated in Table 3. The ‘In-blow test’ is a first measurement of temperature and carbon content (typically at ~0.3% C) in order for the operator to determine the current conditions of the vessel and gauge the required oxygen to obtain desired carbon and temperature at the end of the heat. Following implementation of the automatic lance height and flow control and automatic slopping mitigation implemented, slopping events were avoided 100% of the time (see Table 4).

SUMMARY
A holistic approach to steelmaking optimisation and control represents a significant opportunity to improve steel quality and productivity, lower conversion costs, and improve environmental performance and safety. The deeper understanding of the EAF and BOF steelmaking process and operation provided by EFSoP® and iEAF® – iBOF® will contribute greatly towards more efficient operation and to the development of future optimisation strategies for the furnace and the converter. Moreover, when EAF and BOF operations have been optimised, it becomes more difficult and expensive to make even slight improvements in the operating efficiency. At this point the biggest potential for efficiency improvement in the EAF and BOF is heat recovery from the off-gas. 

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<table>
<thead>
<tr>
<th>Items</th>
<th>% change</th>
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<tbody>
<tr>
<td>Carbon addition</td>
<td>-2.7</td>
</tr>
<tr>
<td>Al deoxidant</td>
<td>-4.0</td>
</tr>
<tr>
<td>Ferroalloys</td>
<td>-1.6</td>
</tr>
<tr>
<td>Oxygen consumption</td>
<td>-0.7</td>
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Table 1 Consumption benefits due to end point prediction and catch carbon practice implemented

<table>
<thead>
<tr>
<th>BOF vessel</th>
<th>Average carbon %</th>
<th>s.d. (%)</th>
</tr>
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<tbody>
<tr>
<td>Without iBOF</td>
<td>0.108</td>
<td>0.059</td>
</tr>
<tr>
<td>With iBOF</td>
<td>0.092</td>
<td>0.025</td>
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</table>

Table 2 Catch carbon performance

<table>
<thead>
<tr>
<th>C prediction error s.d. (points)</th>
<th>T prediction error s.d. (°C)</th>
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<tbody>
<tr>
<td>End point</td>
<td>1.4</td>
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<tr>
<td>In blow</td>
<td>25</td>
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Table 3 End point C and T prediction

<table>
<thead>
<tr>
<th>Prediction</th>
<th>% of heats</th>
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<tr>
<td>Slopping predicted correctly</td>
<td>87.6</td>
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</table>

Table 4 Slopping prediction (without corrective action...data acquisition phase)