Water Detection & Process Optimization using *Intelligent* EAF Technology at SDI Pittsboro IN

M. Khan[1], E. Uchiteleva[1], V. Scipolo[1], C. Meidell[2]

[1]Tenova Goodfellow Inc.
10 Kingsbridge Garden Circle, Suite 601, Mississauga, ON L5R 3K6 Canada
Tel: +1 (905) 507-3330 Fax: +1 (905) 507-3353
E-mail: vittorio.scipolo@tenova.com

[2]Steel Dynamics, Inc.
8000 N County Rd 225 E, Pittsboro, Indiana 46167
Tel: +1 (317) 892-7201
Email: colin.meidell@steeldynamics.com

Keywords: Intelligent EAF, Process Optimization, Water Detection, NextGen, Off-gas

ABSTRACT

Lower costs, increased productivity & yield, reduced emissions and maintaining safety are key drivers for all EAF operations. The recent installation of a NextGen® hybrid laser/extractive off-gas system together with *i*EAF® process control software at SDI Pittsboro has demonstrated significant reductions in electrical & chemical energy, electrode consumption and GHG emissions. Improved safety by early detection of numerous actual EAF water leaks was also achieved using NextGen® full-spectrum off-gas analysis (CO, CO_2, H_2, O_2 and H_2O vapor), as measured at the 4th hole and downstream in the fume system. This paper will focus on confirmed operational and safety benefits realized at SDI Pittsboro.

INTRODUCTION

Steel Dynamics Inc., ("SDI") - Engineered Bar Products Division, located in Pittsboro, Indiana, is a state-of-the-art industry facility supplying special-bar-quality (SBQ) products. The 100 ton top charge EAF produces 750,000 tons annually of the highest-quality cast products. Due to the markets supplied by SDI, a wide variety of grades are produced which necessitates a wide variety of scrap mixes and melting practices. Maintaining and optimizing a static melting and chemical energy program in this operating climate is very difficult. Runs of any given scrap mix are typically short and do not offer time for the furnace operator to find the 'sweet spot' on a given day. SDI believed that dynamic control of the furnace would offer a superior way to maximize efficiency even in the face of inconsistent scrap mix and steel grade production.

Tenova's industry leading "Intelligent EAF" (*i*EAF®) technology platform is summarized in Figure 1 and incorporates three main streams:

1. Innovative and patented **NextGen® off-gas analysis hardware & sensors** that provide actual measurements in critical process areas and thereby avoid control errors and inaccuracies that can result when using estimates and assumptions. Full Spectrum off-gas composition (CO, CO_2, H_2, O_2 and H_2O vapor) and off-gas flow, temperature and pressure sensors provide valuable real-time measurements needed for Water Detection and a real time EAF mass & energy balance;
2. Proprietary ***i* EAF® Software** designed to provide performance benefits from reduced energy and increased productivity as well as effective water detection with low false alarm rate in both an oxidizing and reducing EAF;
3. ***i*EAF® Service & Support Program** that now includes a breakthrough Industry 4.0 cloud based computing program for continuous system monitoring, dynamic model retuning and continuous improvement.

Each component of the platform is further described in references [1, 2].

At SDI Pittsboro, the following Tenova technologies were applied to achieve lower costs, increased productivity and yield:

- Off-gas analysis, flow and temperature with NextGen® hardware & sensors,
- *i* EAF® performance savings models - Module 1 for dynamic control & optimization of the quantity of chemical energy and Module 2 for dynamic control of both electrical and chemical set point timing on the basis of the actual energy received by the charge after losses

As well, Tenova's Water Detection System (WDS) hardware and water detection models were employed to improve safety by early detection and alarming of numerous actual EAF water leaks.

This paper presents the confirmed operational and safety benefits realized at SDI. Additional novel algorithms to detect and alarm for EAF water leaks are also presented.

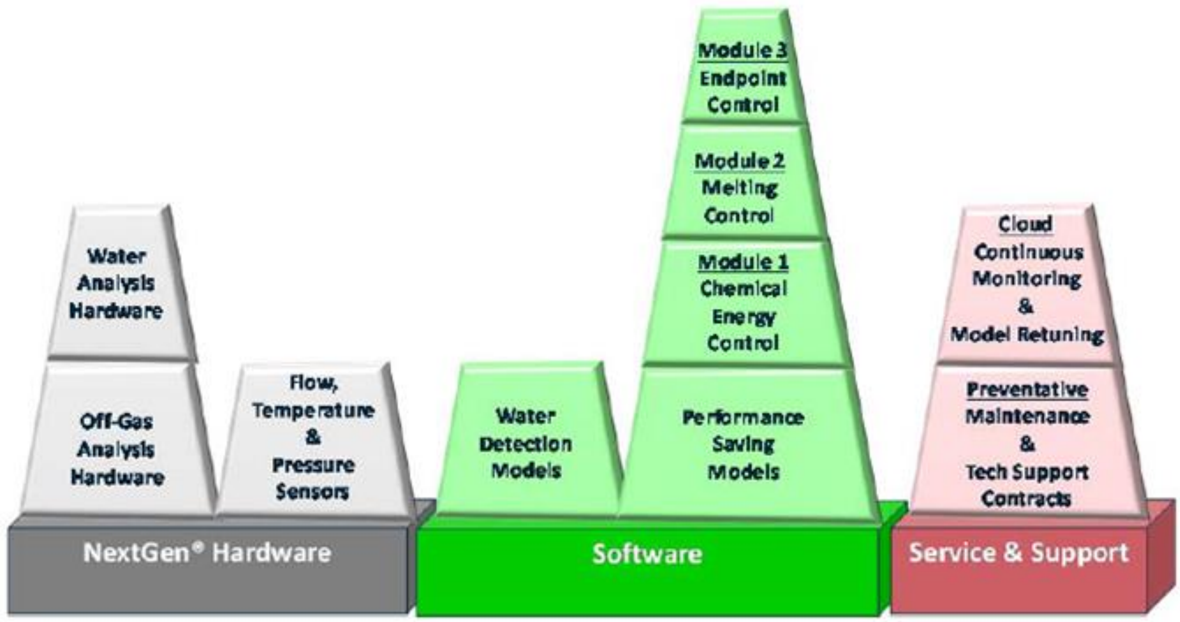

Figure 1. Tenova's *i* EAF® technology platform

TENOVA *i* EAF® SYSTEM AT SDI PITTSBORO

The Tenova *i* EAF® system consists of hardware and software that controls equipment of the EAF operation including burners, lance oxygen injectors, carbon injectors, electrical input and fume system flow. Figure 2 shows the key components and communication scheme of the Tenova *i* EAF® system at SDI Pittsboro, which consists of the following:

1. NextGen® hardware and sensors including
    a. A NextGen® Off-Gas Analysis System consisting of single Central Control Cabinet and Two Sampling / Analysis Stations (upstream and downstream)
    b. Tenova's proprietary optical off-gas temperature camera
    c. Tenova's proprietary optical off-gas velocity sensor
2. *i* EAF® Control Server, HMI, models and software

Details of the NextGen® hardware and sensors are described in reference [1]. The NextGen® Server is inside the Control Cabinet and collects gas measurements as well as operating information from the two Sampling/Analysis Stations, the temperature camera and the velocity sensor. The NextGen® Server contains software to display this information and to control the operation of the NextGen® Gas Analysis System.

The *i* EAF® Server collects existing process information from the SDI PLC network as well as new gas measurements provided by the Tenova hardware for input into Tenova's iEAF® real-time mass & energy models, which then generate optimized set points and set point timing for the equipment to be controlled. The *i*EAF® Server contains software that displays relevant process, control and system alarm information via its HMI functionality.

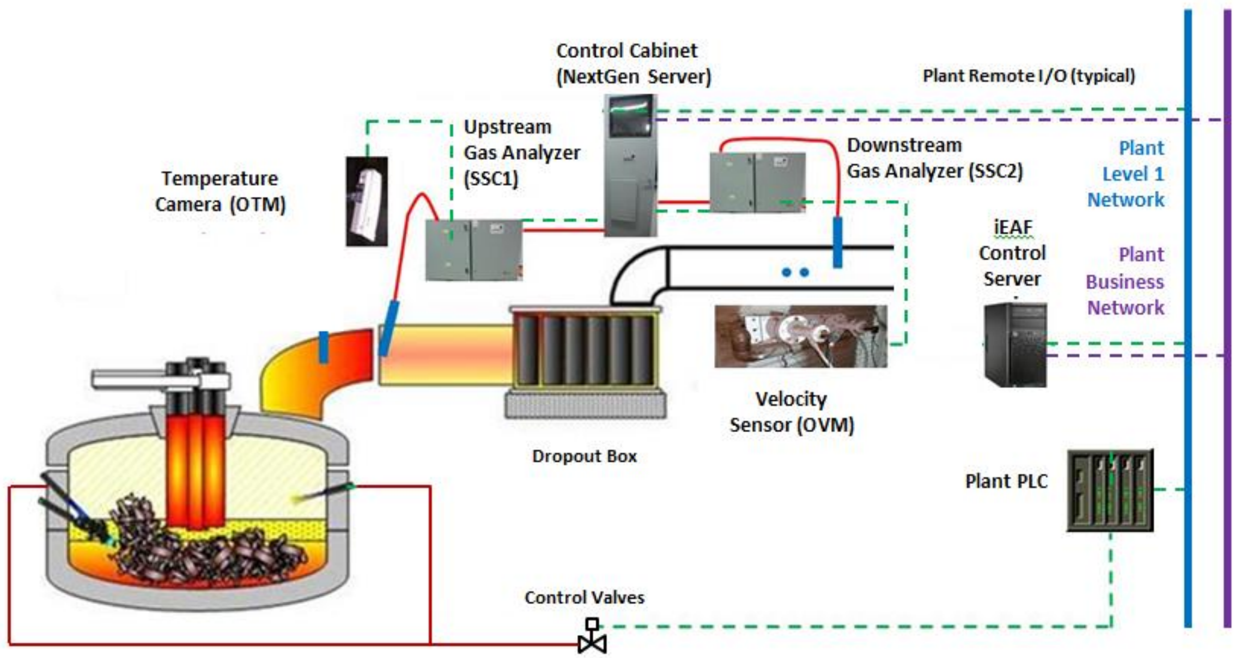

Figure 2. Tenova *i*EAF® system at SDI

OPERATIONAL COST SAVINGS

*i*EAF® Module 1 and Module 2 were used to achieve lower costs, increased productivity and yield at SDI. Both modules work together to control and optimize each heat's energy inputs as follows:

- MODULE 1 uses NextGen® full spectrum off-gas analysis to dynamically control and optimize the "quantity" of chemical energy added to the EAF. As shown in Figure 3, Module 1 is effective in both reducing and oxidizing freeboard conditions - it dynamically controls chemical energy inputs with the aim of establishing a more neutral, slightly reducing freeboard chemistry;
- MODULE 2 uses a real-time Mass & Energy Balance calculated second-by-second from start-to-end of the heat using actual measurements from the NextGen® analyzer, off-gas sensors and with heat specific data from a PLC link. The M&E Balance is used to determine the actual "Net" Energy received by the charge and bath after allowance for actual energy losses in the off-gas, the slag, and the cooling circuit. Unlike more traditional kWh per ton control which essentially paces every heat the same way without regard for each heat's actual energy efficiency, Net Energy control is a major breakthrough that dynamically controls furnace pacing based on each heat's specific energy inputs, inefficiencies & losses. Using Net Energy, Module 2 can precisely calculate the "Melting Progress" (MP) which provides information on the proportion of the charge that has melted on a second-by-second basis as well as the onset of flat bath conditions that signal the start of refining.

$$\textbf{MP} = \frac{\text{Net energy to charge}}{\text{specific energy required to melt} * \text{charge weight}}$$

$$\textbf{MP} = \frac{\text{Electrical} + \text{Burner} + \text{Oxidation} - \text{OG sensible \& chem. losses} - \text{WC}}{\text{charge weight} * \text{specific energy required to melt}}$$

The *i*EAF® software, Module 1 and Module 2 are further described in references [1, 3].

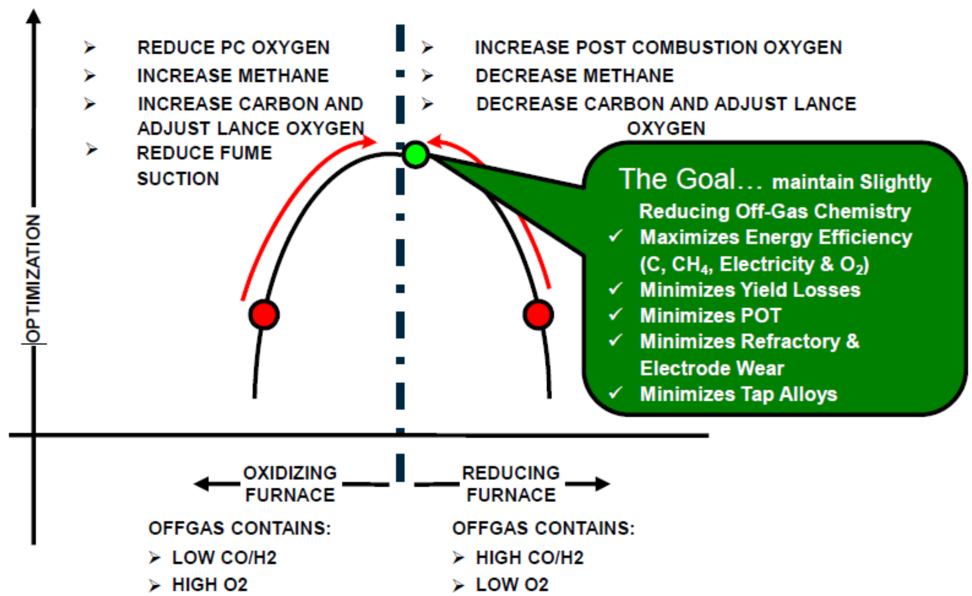

Figure 3. Objective of *i* EAF® Module 1

Operational savings achieved at SDI with *i*EAF® & NextGen® system are shown in Table 1. Significant electrical, natural gas and charged carbon savings were achieved with some small increase in oxygen and injected carbon consumption. The net result was a 3.6% reduced consumption cost for these 5 parameters. In addition, yield and power-on-time were significantly improved. Overall, these savings far exceeded the return of investment expected for the project by SDI management.

Also, the addition of *i* EAF® technology has allowed for better understanding of the furnace performance across each unique scrap mix. At SDI, one mix in particular has been transformed from one of the lowest performing and most inconsistent scrap mixes to among the highest performing due to better control and utilization of the available chemical energy in the charge.

Table 1. *i* EAF® operational savings achieved at SDI

Parameter	**Saving Result**
Electrical consumption	4.4%
Oxygen consumption	-4.2%
Natural gas consumption	11.3%
Charged carbon consumption	7.1%
Injected carbon consumption	-0.7%
Consumption cost	3.6%
Yield	0.8%
Power on time	0.4 min

WATER DETECTION AT SDI

It is important to differentiate between normal and abnormal water conditions in the EAF. Water is normally present in the EAF from humidity in ambient air sucked into the furnace by the draft control system, from moisture in scrap and other charge materials, from moisture generated by the combustion of natural gas, and from electrode spray water. Abnormal humidity in the EAF is caused by unexpected input of water to the system that creates potentially unsafe operating conditions. For example, such water can be a result of excessive moisture trapped in the scrap due to heavy rain or snow. However, a far more concerning condition for EAF steelmakers is cooling water leaks from the panels or burners, in particular, voluminous leaks that can occur suddenly especially during melting and flat bath conditions. Whenever a leak is large enough to create a pool of liquid water on the surface of the slag, there is an opportunity that a slosh event will cover the pooled water with molten slag and steel thereby creating a steam explosion, which can cause a second more severe H_2 and CO explosion.

A properly functioning off-gas analysis system together with a properly tuned model that identifies when the actual measured water in the off-gas exceeds the expected water is capable of providing real-time alerts to the EAF operator when abnormal water conditions are present. It is important to appreciate that while the off-gas water detection system cannot be considered a failsafe safety system that can be relied 100% upon to detect every leak and not to occasionally false alarm, it has been shown capable of warning operators of an impending and potentially significant safety issue in many operating situations.

Based on a rigorous analysis, Tenova has identified the following important criteria necessary for an EAF off-gas water detection system:

1. A fast, reliable off-gas analyzer that provides uninterrupted analysis whenever power is on. If the analyzer signal is interrupted for any reason, the water detection system will be ineffective;
2. Full spectrum off-gas chemistry measurements are recommended; however, analysis of H_2O vapor, H_2 and CO is considered mandatory. H_2 and CO are particularly important for detecting water leaks when the EAF freeboard chemistry is reducing whereas H_2O vapor is important if the freeboard chemistry is oxidizing;
3. A reliable and precise predictive water model capable of calculating the expected water in the furnace second-by-second throughout a heat;
4. An alarming algorithm that is tuned to the specific furnace and operating conditions and is capable of both minimizing false alarms and of quickly alarming whenever there is a strong probability that the actual water in the EAF exceeds the expected water determined from the predictive water model; and,
5. The ability to sample and process data in real time, to have reliable communications that ensure data availability, as well as to have storage capacity in order to archive the information for offline analysis

References [4, 5] elaborate in more detail on EAF water detection theory, on the motivation for full spectrum off-gas analysis, on Tenova's Water Detection System (WDS) hardware/sensors/software as well as on the predictive and alarming water detection models. The following section provides a short summary of previous work and also expands on an additional algorithm that has recently been developed based on observations of various real panel and burner leaks at SDI.

Background Overview

Figure 4 shows the core components of Tenova's WDS based on a predictive water model. The first core component is the predictive model that estimates the expected levels of the H_2O during normal operating conditions. The predictive model relies on the full spectrum off-gas chemistry, temperature and flow measurement from the NextGen® gas analyzer and sensors along with actual operating and process information. The second core component monitors the measured H_2O in the off-gas provided by the NextGen® gas analyzer as well as its behaviour. An analysis of the difference between the predicted and measured H_2O provides the basis to detect and alert for abnormal water in the EAF. A warning or an alarm is sent to the EAF operator based on the severity and duration of the event.

Figure 5 summarizes the detection and alarming scheme based on the difference between the predicted and measured H_2O. The blue line represents the actual H_2O concentration in the off-gas measured by the NextGen® System. The dotted grey line represents the H_2O prediction with Tenova's proprietary predictive water model. The red dotted line is a threshold H_2O level that is calculated by adding a constant value (a tunable parameter) to the prediction value. This threshold represents a confidence level that there is abnormal water currently in the EAF. Once the measured value exceeds the threshold value, the system starts monitoring the difference. Tunable alarming metrics are used to provide additional confidence levels that the abnormal water event is valid. An operator warning is the first indication of a potential abnormal water event and then an operator alarm is provided if the abnormal water event further persists. The parameters of the predictive water model and the alarming algorithm are expertly tuned for each EAF based on an in-depth analysis of the specific operation and behaviour of the off-gas measurements. The WDS is initially tuned using controlled water injection trials (simulated water leaks) designed to optimize detection and alarming response time to warn of abnormal water levels in the EAF while at the same time minimizing the false alarm rate.

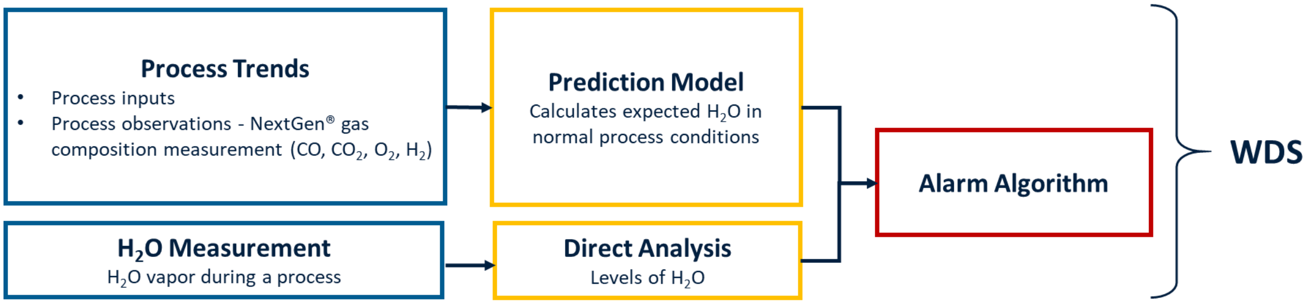

Figure 4. Components of the predictive H_2O-based WDS

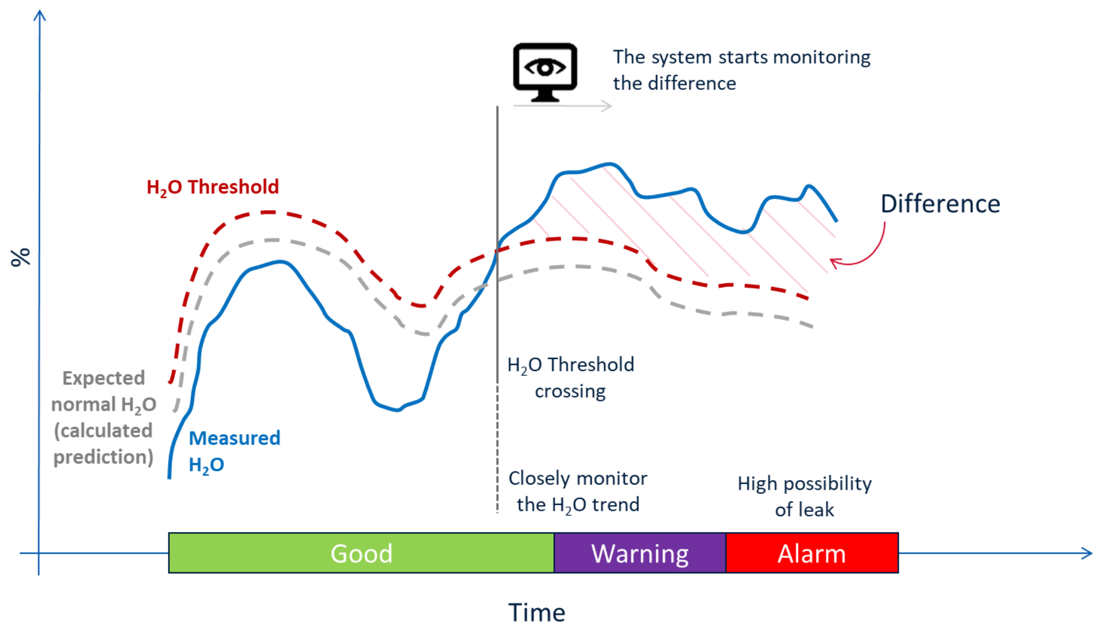

Figure 5. Detection and alarming scheme for predictive H_2O model algorithm

New Detection and Alarming Algorithms

In addition to the WDS predictive water model and alarm algorithm described above, new algorithms have been developed and implemented at SDI. These new algorithms track other behaviors of water in the EAF and are based on a direct analysis of the behavioral changes of H_2, CO and H_2O vapor off-gas chemistry measurements. This addition to the predictive water model and alarm algorithm reduces the response time and improves the confidence level of the overall WDS.

As shown in Figure 3, a mildly reducing freeboard chemistry represents the most efficient and lowest cost EAF operation mode. Whenever the freeboard is reducing, the off-gas H_2 to CO ratio has been observed to be a critical variable necessary for predicting and alarming for abnormal water in the EAF. Most importantly, Tenova's NextGen® System is the only laser based off-gas analyzer technology capable of measuring H_2 and CO.

During normal reducing furnace operating conditions, typically the H_2 to CO ratio is less than 1. When there are abnormal water conditions in a reducing EAF, the H_2 to CO ratio can spike above 1. Figure 6 illustrates Tenova's H_2 and CO ratio-based detection and alarming scheme, which represents an added layer of detection capability over the predictive water-based approach shown in Figure 5. Whenever the H_2 to CO ratio exceeds unity, Tenova's water detection system starts monitoring the magnitude and duration of the event and employs furnace specific criteria to trigger a warning and then an alarm while minimizing the false alarm rate.

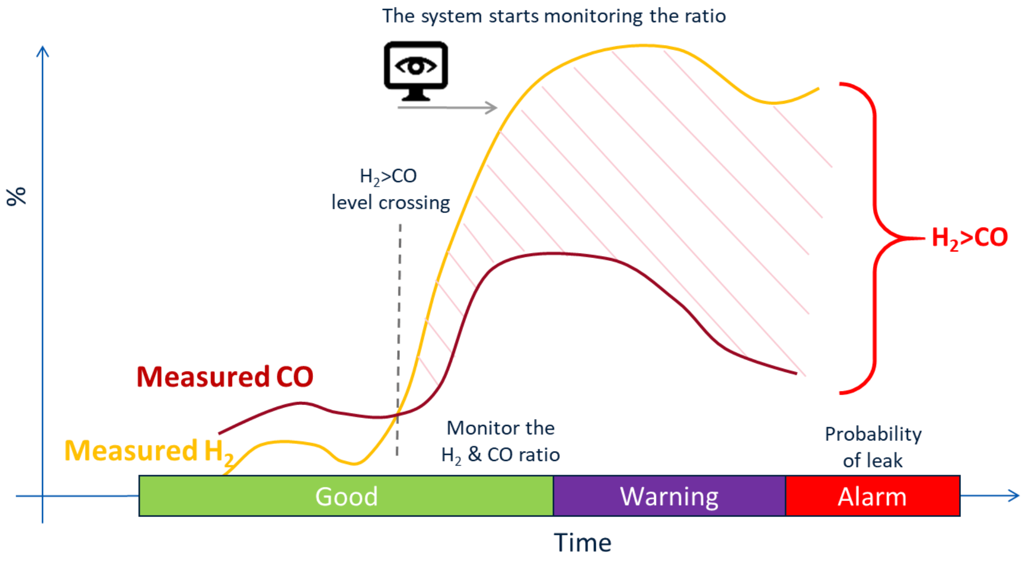

Figure 6. Detection and alarming scheme for H_2 and CO ratio algorithm

The aforementioned algorithm as well as other proprietary algorithms work as separate sub-routines within Tenova's WDS and generate independent operator warnings and alarms when abnormal behaviors of water in the EAF are detected. Figure 7 shows the core components of the combined WDS. The combined algorithms improve the response time and detection capability of the Tenova WDS.

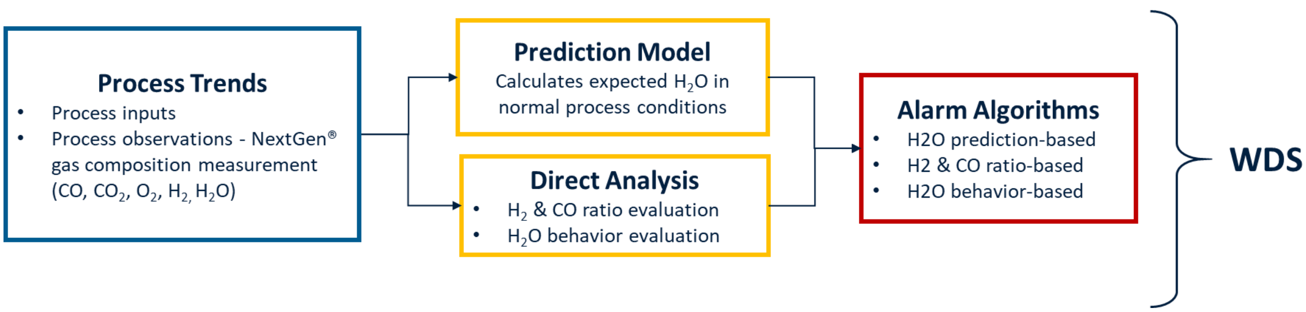

Figure 7. Core components of the combined Tenova WDS

WATER DETECTION RESULTS AT SDI

The development and addition of new WDS algorithms has improved the NextGen®'s detection and response time to real panel and burner leaks at SDI. The development and tuning campaign took several months in order to capture real water leaks since controlled water injection trials were not feasible at SDI.

To date, a number of actionable leaks from several sources have been promptly detected and alarmed by the WDS. The WDS also has a very low false warning rate and false alarm rate at 1.7% and 1.0%, respectively. SDI has implemented a live, real time display of the water detection trends, warnings and alarms to the operators, which allow the operators to make quick informed decisions about potential leaks.

Figure 8 shows an example of typical off-gas chemistry during normal 2-bucket operation at SDI. The absence of O_2 for most of the heat and the presence of CO and H_2 confirm that this heat has a reducing freeboard chemistry. There are no anomalies in the H_2 to CO ratio and the H_2O vapor analysis that would cause the Tenova WDS to trigger a water leak warning or alarm.

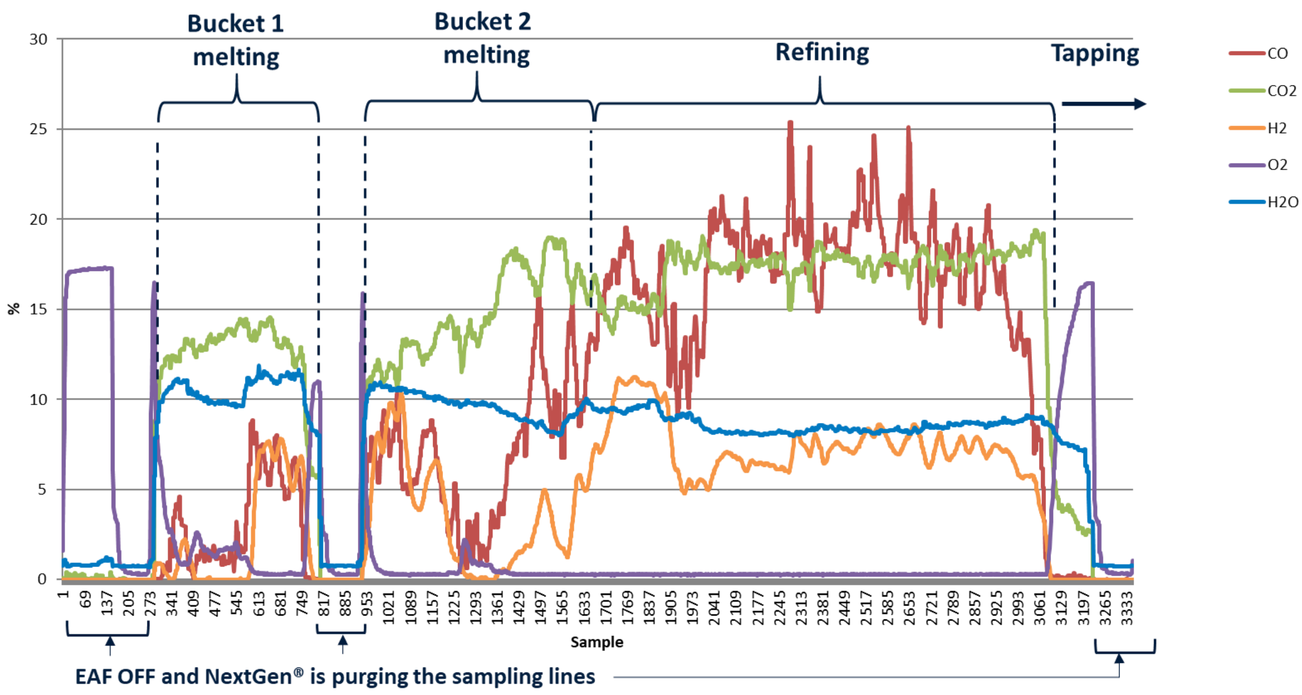

Figure 8. Example of normal chemistry at SDI

By comparison, Figure 9 demonstrates a burner leak and the activation of the H_2O prediction-based alarm. In this figure, the blue curve corresponds to the NextGen® H_2O vapor measurement, and the burgundy curve represents the threshold H_2O level based on the Tenova's WDS predictive model and tuned confidence parameter. The figure shows a sharp step-like increase in the NextGen® H_2O vapor measurement in the middle of melting of the second bucket. Once the measurement exceeds the threshold value, the System starts monitoring the difference between the curves and issues a prediction-based warning to operators after 109 seconds, followed by a full operator alarm 37 seconds later.

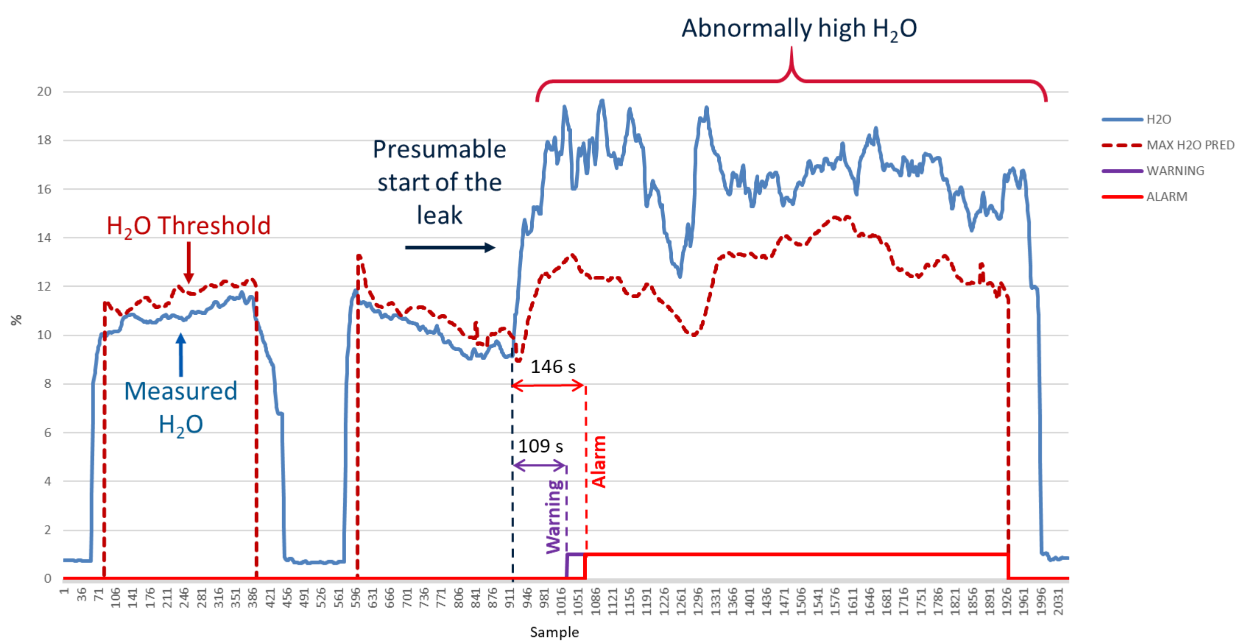

Figure 9. Example of a real leak and the reaction of the H_2O prediction-based algorithm

In a similar fashion, Figure 10 shows the reaction of the WDS to a sudden increase in H_2O concentration. As can be seen in the figure, the algorithm reacted and alarmed in just 12 seconds from the time when the leak becomes visible to the System. This rapid response is vitally important for detecting large leaks.

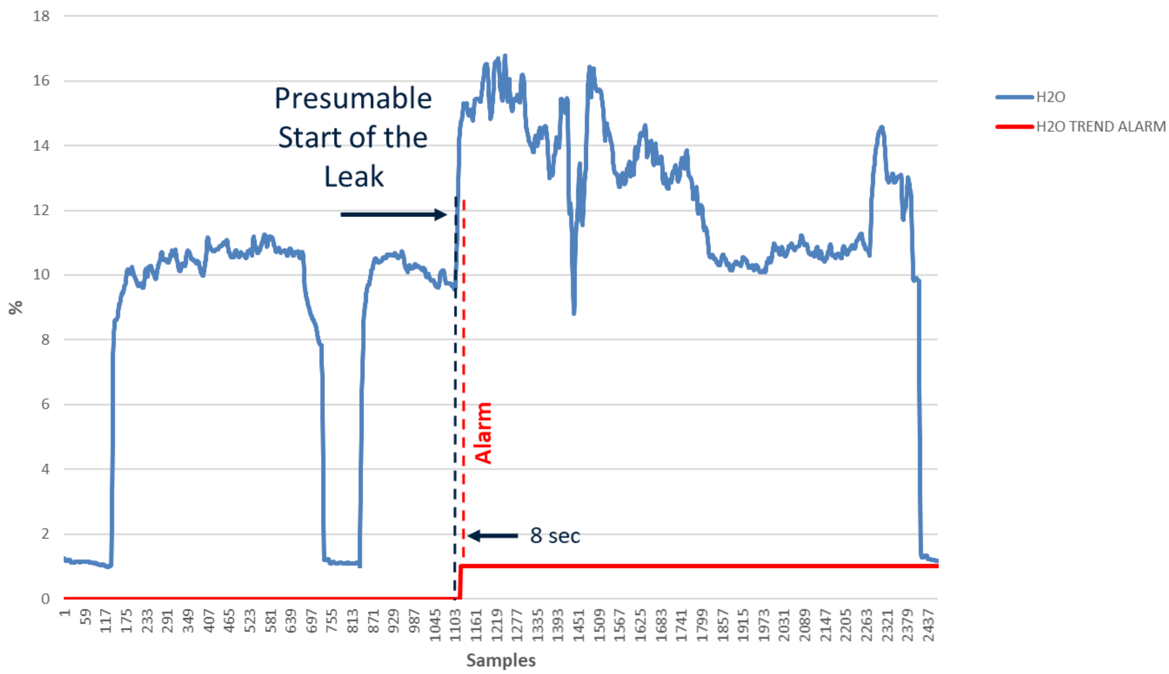

Figure 10. Example of a response to a sudden and large water leak

Figure 11 shows another leak with a clear H_2 response. This example demonstrates the H_2 to CO ratio-based detection algorithm offered only by Tenova's NextGen® System. In the figure, the blue trend represents the measured H_2O, the burgundy and orange curves represent the CO and H_2 measurements. In this case both WDS algorithms: change in H_2O vapor and the H_2 to CO ratio provided clear confirmation of a water leak. An operator warning and a subsequent operator alarm were issued after 128 and 153 seconds, respectively.

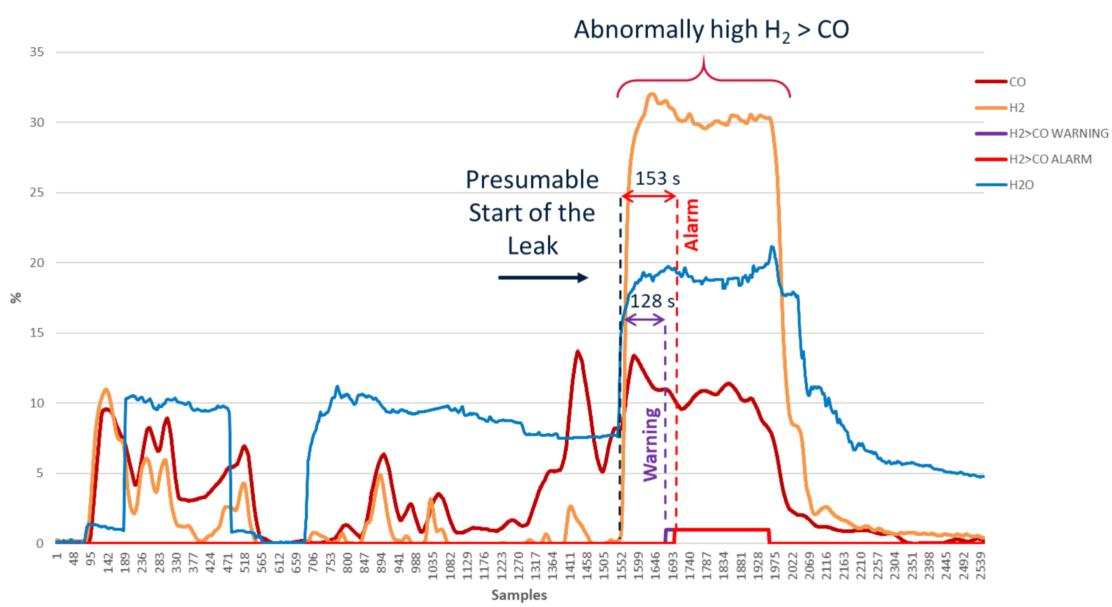

Figure 11. Example of a real leak with high H_2 response

CONCLUSIONS

Tenova's NextGen® hybrid laser/extractive off-gas analysis system has been successfully installed together with Tenova's breakthrough *i*EAF® process control technology at SDI Pittsboro. The *i*EAF® Module 1 technology utilizes NextGen® analysis and a PLC link to dynamically control and optimize the quantity of chemical energy inputs. The *i*EAF® Module 2 technology uses additional sensors and a real-time Mass & Energy Balance to dynamically control both electrical and chemical energy set points based on the actual Net Energy received by the charge after allowance for actual energy losses.

SDI Pittsboro confirms significant operational savings have been achieved with this Technology package including 3.6% reduced consumption costs, a 0.8% increase in yield and a 0.4 minute reduction in power-on-time. The operational benefits and cost savings have exceeded the return of investment expected by SDI management.

Tenova's Water Detection System is the only laser based off-gas analysis system to measure H_2, H_2O vapor and CO which has been shown to be critical for rapid and precise water leak detection in all operating situations. Tenova's WDS algorithms have demonstrated consistent detection and rapid response time to real panel and burner leaks. At SDI Pittsboro, a number of actionable leaks from several sources has been promptly detected and alarmed by the WDS. The WDS also has a very low false warning rate and false alarm rate at 1.7% and 1.0%, respectively. SDI has implemented a live, real-time display of the water detection trends, warnings and alarms to the operators, which allow the operators to make quick informed decisions about potential leaks.

REFERENCES

1. Doug Zuliani and Vittorio Scipolo "Advancements in Tenova's NextGen® Off-Gas based Process Control Technology Platform", AISTech 2020.
2. Vittorio Scipolo and Doug Zuliani, "Industry 4.0 – The Evolution of Intelligent EAF Steelmaking", METEC 2019 Dusseldorf, Germany, June 25-29, 2019. https://www.researchgate.net
3. Harish Iyer, Babak Babaei, Vittorio Scipolo and Cameron Cossette; "EAF Optimization using real-time Heat and Mass Balances at Nucor Steel Seattle", AISTech 2017, Nashville Tn., May 8-11, 2017.
4. M. Luccini, V. Scipolo, D. Zuliani and L. Poli; "Water Leak Detection in EAF based on Tenova's Off-Gas Technology: Recent Developments and Results in Lucchini RS, Lovere, Italy", AISTech 2017, Nashville Tn., May 8-11, 2017. https://www.researchgate.net
5. Harish Iyer, Vittorio Scipolo and Cameron Cossette; "EAF Water Detection at Nucor Steel Seattle using Tenova's NextGen® Off-Gas Analysis Technology", AISTech 2018, Philadelphia Pa., May 7-10, 2018.