Tenova's *Intelligent* EAF Technologies Aligned To Industry 4.0 Standards

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Summary

The recent development of smart technology and high-speed computer analysis, is rapidly reshaping the traditional EAF process into one that is closely controlled, more predictable and optimized in real-time. Concrete steel plant examples of the deployment of an array of innovative technologies that have enabled dynamic process optimization and dramatically reduced total energy consumption, increased yield and decreased power-on-time will be discussed. Also, innovative sensors coupled with computerized data analysis that is providing breakthrough solutions to chronic problems such as water leak detection and dynamic process control for each stage of the melting and refining process

Introduction

The aim of Industry 4.0 is the creation of smart factory that utilizes a highly digitalized link between production equipment, sensors, Level 1 & 2 control networks, process control models and cloud computing both within specific process steps and across the entire production facility. The net result allows for more effective control & optimization of each process step in a way that is dynamically aligned with changing day-to-day factory constraints thereby minimizing total production costs & inefficiencies.

Herein is described, Tenova's vision for Industry 4.0 as it applies to the creation of an "Intelligent" EAF (***i* EAF®**) steelmaking process. The intent of the *i* EAF® technologies is to continuously monitor and dynamically control to sustain optimal performance day in and day out. In addition, *i* EAF® technology fits within Tenova's ***i* MeltShop®** . Industry 4.0 system to ensure that EAF production is harmonized to meet the plant's daily production constraints thereby achieving the optimum result for the entire steel shop. [1]

The objective is to implement an Industry 4.0 EAF solution that provides continuously improved EAF savings & performance based on:

- Replacing assumptions & related inaccuracies with real-time process measurements in critical areas obtained from robust, reliable sensors;
- Replacing statistical process models which are prone to excessive drift with a new generation of more fundamental thermodynamic & kinetic based process control models that incorporate real-time mass & energy balances;
- Creating a digitalized interface that links process equipment, sensors, Level 1 & 2 networks, and process control models;
- Using cloud computing services to store and analyze large amounts of process data from multiple EAF's & plants where appropriate;
- Employing a team of highly trained data scientists together with machine learning techniques to develop improved & optimized 2nd & 3rd generation process control models;

- Continuously monitoring model performance; and,
- Providing automatic dynamic retuning of the models when necessary to ensure sustained maximum performance over the long-term.

Intelligent EAF – STEP 1 Critical Sensors

Implementation of robust sensors is an important first step in establishing a workable, EAF, Industry 4.0 solution. The sensors provide actual measurements in critical process areas and thereby avoid control errors and inaccuracies that can result when using estimates & assumptions. Off-gas composition, flow, temperature & pressure provide valuable real-time information necessary for closing a real time EAF mass & energy balance, for optimized control of the quantity & timing of both chemical energy & electrical inputs and for optimized furnace draft control. While reliable off-gas sensors have largely been lacking in the past, as explained below Tenova Goodfellow has now developed a full suite of commercially robust sensors that provide these critical process measurements.

A. Full Spectrum Off-Gas Analysis:

Virtually 100% of EAF off-gas consists of 6 species; CO, CO_2, O_2, H_2, H_2O vapor & N_2. Knowledge of this full spectrum off-gas analysis is important for controlling the EAF's oxygen potential, for dynamic control of fume system suction, to enable efficient O_2 lancing & carbon injection, to close a real-time Mass & Energy Balance and for real-time Water Detection which all together dramatically improve EAF energy efficiency, reduce operating costs, improve yield & productivity and improve safety [2].

Traditionally there have been two classes of off-gas analysis technology utilized in EAF steelmaking:

i. Extractive, and,
ii. Insitu Tunable Diode Lasers (TDL)

Both technologies were commercialized about 20 years ago but neither has provided a complete off-gas analysis solution for steelmaking process conditions [3, 11].

In 2015, Tenova Goodfellow developed and patented the 1st commercial "next generation" hybrid extractive/ laser off-gas analysis system designed especially for harsh industrial processes such as exist in EAF & BOF steelmaking [3, 11]. **NextGen®** technology combines the excellent reliability of traditional extractive technology with the faster response time and the lower hardware installation costs of tunable diode lasers. Unlike Insitu systems, NextGen® hybrid technology utilizes off-gas extraction through a redesigned probe positioned directly in the cone of off-gas exiting the EAF at the 4th hole.

Positive extraction remains the best way to ensure high system reliability and avoid lost analytical signals. Compact Extractive Sampling Station(s) are mounted directly on the melt shop floor without the need for an environmentally protective room. A short heated line connects the Sampling Station to the gas sampling probe. Since the Station is compact in size, it can be located in close proximity to the probe thereby shortening the physical distance and time delay associated with transporting the off-gas sample to the analytical cells. The Extractive Sampling Unit has a high speed pump to rapidly & continuously extract the off-gas sample through the probe located in the cone of pure EAF off-gas flowing in the duct. The unit then filters the gas sample to remove particulate matter prior to analysis. The clean gas is then introduced into various types of laser & analytical cells to reliably analyze the off-gas for CO, CO_2, O_2, H_2 & H_2O vapor. Using clean filtered off- gas minimizes analytical cell maintenance. Also filtered gas ensures that there are no analytical signal interruptions as is the case with Insitu lasers.

Each extractive sampling station is connected by fiber/coax cable(s) to a compact multipoint central control cabinet that is most often located in the EAF control room. This central unit physically houses the laser beam generators. It sends continuous laser signals via fiber optic cable to each Extractive Sampling Station's analytical cells and receives the return signals by coax cable to continuously analyzes full-spectrum off-gas chemistry for CO, CO_2, O_2, H_2, H_2O vapor & N_2 (by difference from 100%).

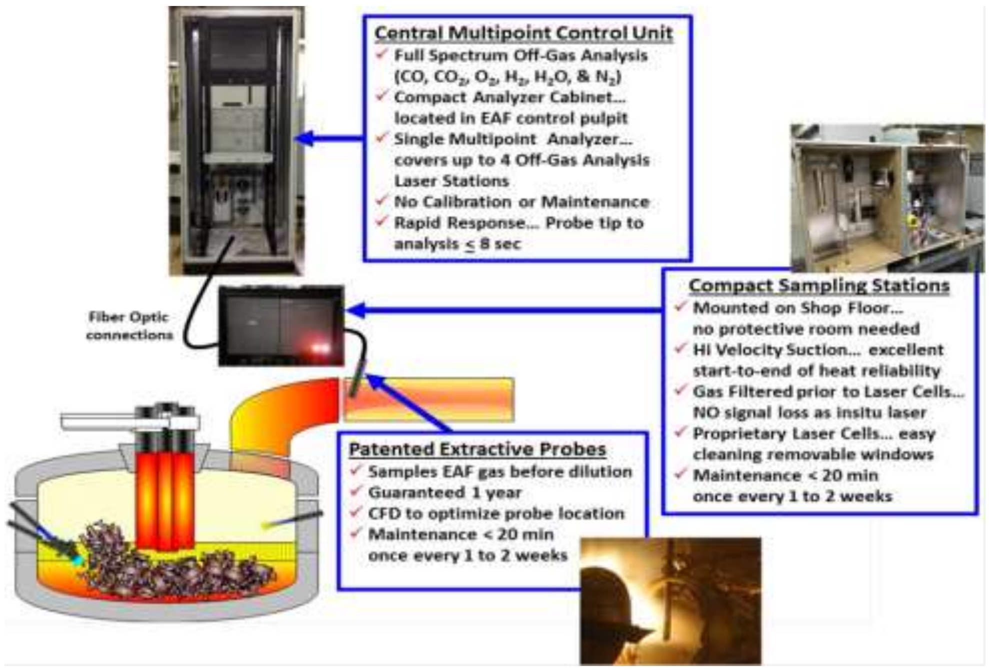

Figure 1: NextGen® Multipoint Hybrid Extractive/Laser Technology

Importantly, NextGen® technology has excellent multipoint capabilities and can be connected to up to as many as 6 independent Extractive Sampling Stations. NextGen® uses a beam splitter to divide the main high powered laser signal into multiple continuous lower powered beams. Because Insitu laser systems require a full powered beam to minimize signal interruptions, they need to use an optical switch to sequentially index the full powered main beam from one sample location to the next. As such, Insitu laser systems provide a series of discrete analyses (8 seconds between individual readings for 2 sample locations, 12 seconds for 3 sample locations & so on). By comparison, beam strength is not a concern with NextGen® because there are no beam interruptions when using filtered gas. Hence, NextGen® seamlessly provides "continuous & simultaneous"off-gas analysis from multiple sampling locations. NextGen® technology is ideally suited for multiple sampling applications – NextGen® installations since 2015 include:

- 4 Systems in top charge EAF shells equipped with upstream & downstream off-gas analysis [5]
- 3 Systems in shops equipped with BOF & AOD furnaces
- 8 Systems in Consteel®, Twin Shell & Shaft Furnace shops [6,7]

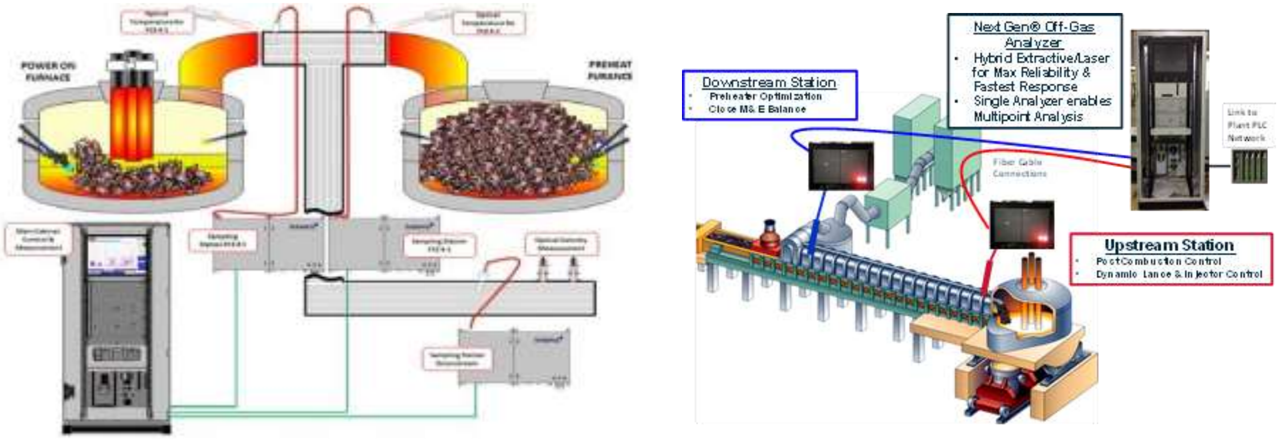

Figure 2: NextGen® Technology in Multipoint Applications

The NextGen® system also offers significantly improved operator safety since there is no off-gas physically at the Central Cabinet thereby removing any concerns from a CO leak in a confined space such as a control room

B. Off-Gas Flow & Temperature Measurement:

Real-time EAF mass & energy balance calculations are powerful process control tools but they require knowledge of not only off-gas % composition but also of off-gas flow and temperature. Contact sensors embedded in the off-gas stream have traditionally been used to monitor off-gas flow and temperature. These contact sensors can suffer from abrasion & thermal degradation that often leads to excessive wear, maintenance & sensor failure.

Because of this, these types of high maintenance contact sensors are often left unrepaired which in turn leads to process control errors & inaccuracies when assumed values are used to replace actual measurements.

To address this problem, Tenova Goodfellow recently developed and commercialized a series of proprietary optical, noncontact sensors to measure both off-gas flow (“**OVM**“) and temperature.(“**OTM**“).

The OVM consists of two small optical sensors attached to optical view ports in the fume duct. These sensors continuously track radiation patterns in the fume stream to measure off-gas velocity. Because there are no components in direct contact with the off- gas stream, the OVM is particularly valuable for measuring high temperature gas flow.

The OTM is an optical sensor that uses a wavelength ratio method to measure off-gas temperature. This design requires minimal maintenance and avoids temperature inaccuracy problems often associated with excessive dust collecting on the optical lens.

The OTM is available in two configurations, either as a remote sensor or as view port sensor (Figure 3).

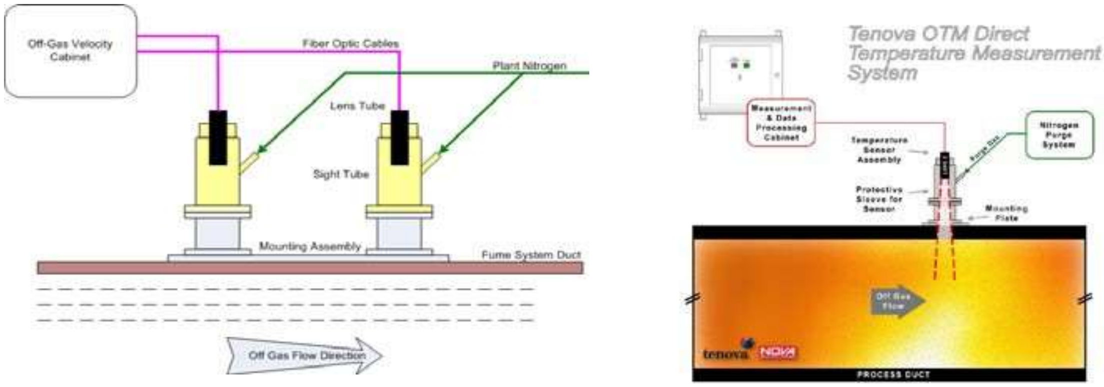

Figure 3: Tenova's OVM & OTM Optical Sensors

C. EAF Static Pressure Measurement:

EAF static pressure is an important measurement for fume system draft control. Tenova Goodfellow's proprietary static pressure probe is mounted on the furnace elbow and is similar in design to the NextGen® off-gas analysis probe. Tenova's pressure probe design has proven to be much more reliable and require less maintenance than more commonly found pressure ports located in the furnace roof. [4]

Intelligent EAF – STEP 2 Fundamental M&E Balance Process Control Models

Typical EAF control is based on 'kWh/ton'. With this conventional method, each heat's sequencing & energy delivery is essentially the same and is made without consideration for chemical energy inputs, and energy losses & inefficiencies - 'Kwh' is fixed by the transformer and 'ton' is fixed by the charge weight.

A better approach is to control the EAF with real-time mass & energy balances – in this case, the timing & quantity of chemical energy ('kWh equivalent') and electrical energy ('kWh') is made dynamically on a heat specific basis allowing for the "actual total net energy" received by the charge after energy losses & process inefficiencies [4,5,8].

Tenova's *i* EAF ® technology utilizes the critical sensors described above together with a link to the plant's Level 1 & 2 network to obtain the measurements needed to close real-time EAF mass & energy balances. As shown in Figure 4, the typical installation arrangement includes:

- A single NextGen® Control Cabinate Connected to Upstream & Down stream Sampling Stations
- OTM optical off-gas temperature sensor
- OVM optical off-gas velocity sensor
- An EAF static pressure probe

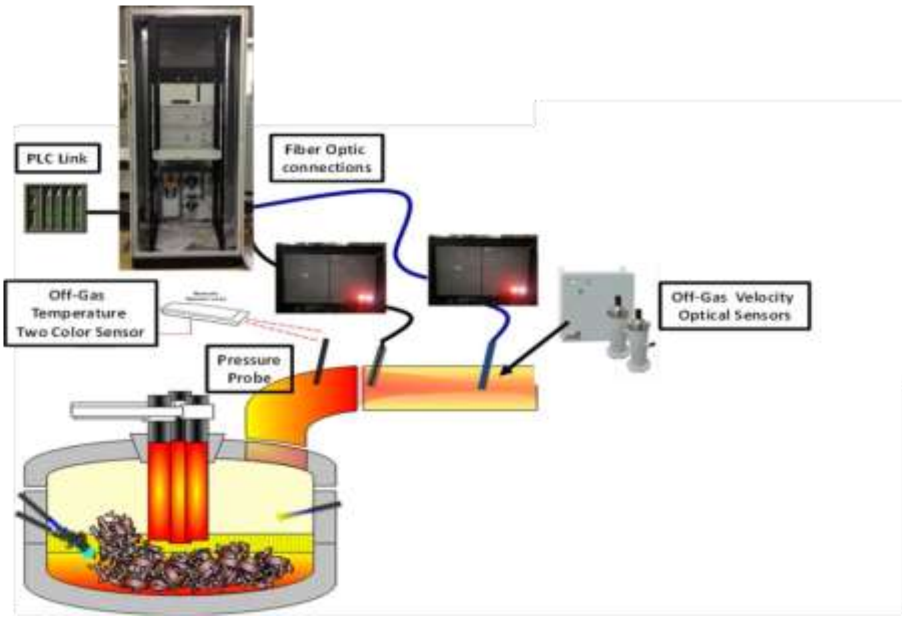

Figure 4: *i* EAF® Typical Hardware Arrangement

The *i* EAF® uses fundamental process control models incorporating thermodynamic & kinetic algorithms and mass & energy balance calculations. When using actual sensor measurements, experience shows that fundamental models offer a higher degree of precision than statistical models which are prone to performance drift as operating conditions change.

The *i* EAF® is programmed with several independent process control models that work independently to evaluate different aspects of the EAF process. [4] Each model contributes to the calculation of the total chemical & electrical "**Net Energy**" delivered to the charge/bath after losses & inefficiencies:

Total Net Energy =

Σ Electrical In + Σ Chemical In

Σ Off-gas Losses – Σ Other Losses

Total Net Energy is calculated second-by-second from start-to end of the heat and is used to dynamically control all energy inputs. The *i* EAF® also uses Total Net Energy to calculate the melting progress of the charge ("%MP") from 0% MP at the start of melting to 100% MP at the flat bath fully melted condition.

The *i* EAF® incorporates three control Modules:

- **Module 1:** controls the quantity of chemical energy input during melting based on the NextGen® full spectrum off-gas analysis;

- **Module 2:** controls the timing for indexing chemical & electrical energy set points during melting based the Total Net Energy delivered to the EAF after losses
- **Module 3:** controls O2 delivery once flat bath conditions exist to hit the aim endpoint %C, ppm O & temperature.

The *i* EAF® includes a web based HMI that can be viewed by authorized users on any PC, tablet or phone connected to the internet. The software has been configured with an exceptionally open architecture allowing an unparalleled level of user customization. The *i* EAF® comes with built in process control algorithms for all standard EAF equipment including burners, lances, injectors, powder feeders, electrical control, etc. The software allows authorized users at the plant to enter additional code in any programming language that can be compiled as a library. As such each plant can customize the basic *i* EAF® software including:

- Modifying existing *i* EAF® process control model algorithms to meet specific user requirements
- Adding new user developed process control models
- Adding control programs for any new or nonstandard EAF equipment including 7 in North America and 6 in Europe & the Middle East.
- Modifying existing HMI screens, adding new HMI screens, generating reports, etc. to meet specific user requirements

While individual plant results can vary, the Average performance benefits with Tenova's *i* EAF® technology across all installations is summarized in the table below:

BENEFITS	STEEL PLANT SIGN-OFF at Project Completion	LATEST COMPLETED INSTALLATIONS	
OPERATING COST	US $ per tls Cost Savings from electricity, carbon, fuels & oxygen	Average Saving Minimum Saving	from $1.47 to $4.25 per tls $1.00 per tls
		Module 1 (Average Saving)	Module 1+2+3 (Average Saving)
ENERGY	Electricity Gas & Fuel Injected Carbon Charge Carbon	8.0 kWh per tls 38.8 sft³ per tls 2.2 lbs per tls 3.1 lbs per tls	15.0 kWh per tls 38.8 sft³ per tls 2.2 lbs per tls 3.1 lbs per tls
	Total In-EAF Energy (kWh equivalent)	24.0 kWh per tls	30.0 kWh per tls
WATER DETECTION	Water Leaks Detected in Real-Time	40L/m	
PRODUCTIVITY	Power On Time – POT Productivity - tls per POT % Yield	Average Saving Average Increase Average Increase	2.0 min per heat 4.6% 0.4%
ENVIRONMENTAL	CO_2 Reduction	Average Reduction	17.9%

Intelligent EAF – STEP 3 Digitalization

Tenova's latest step in developing an Intelligent EAF is an "**EAF Digitalization Program**" implemented by a team of data scientists & process experts using cloud data storage technology and machine learning to monitor & analyze EAF process performance, develop improved process control models and dynamically retune process models.

STEPS 1 & 2 described above created a digitalized interface within the EAF shop that links operating equipment, critical sensors, Level 1 & 2 networks, and *i* EAF® process control models to achieve dynamic mass & energy based control of the EAF process.

The **3rd STEP** completes the **Digitalization** by leveraging on advanced analytics, machine learning methods and Digital Cloud services.

In May 2017, Tenova entered into a partnership with Microsoft® including strategic consulting and Azure cloud computing services. Azure offers superior data security and as well as the most comprehensive compliance portfolio of any cloud provider.

Tenova's Digitalization Program is designed to:

- use the Azure cloud computing services to store and analyze large amounts of process and/or water detection data from multiple EAF's & EAF plants where appropriate;
- employ a team of highly trained data scientists applying machine learning techniques to develop improved & optimized 2nd & 3rd generation process models, i.e. "Digital Twins";
- continuously monitor hardware & process model performance;
- provide automatic dynamic retuning of process models when necessary to ensure sustained maximum performance is maintained over the long-term.

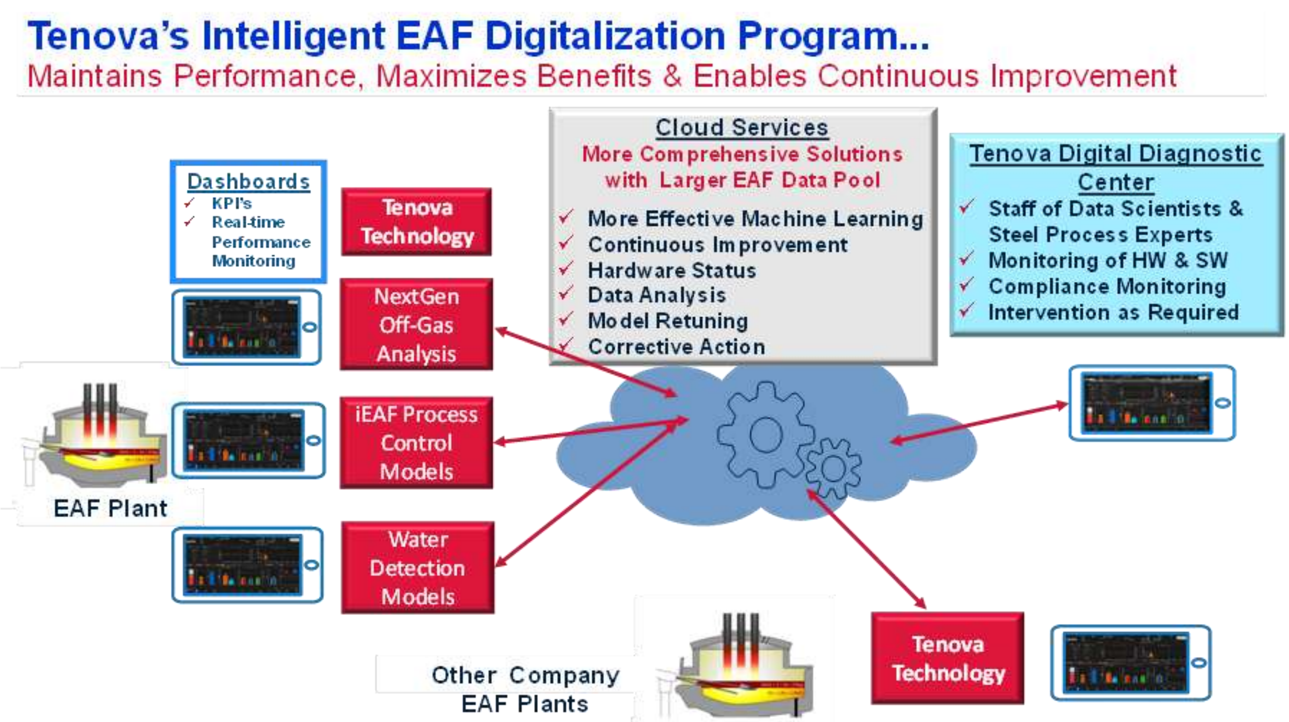

Figure 7: Tenova's Digitalization Program - designed

Tenova's **Intelligent EAF Digitalization Program** is focused on four main areas:

I Continuous monitoring of **NextGen®** system hardware to quickly identify & alert the plant when the equipment requires service & maintenance (see Figure 6)

ii Continuous monitoring & improvement of ***i*****EAF®** process models to sustain & maximize operating performance benefits over the long term (see Figure 7)

iii Continuous improvement of the **NextGen® Water Detection** models to minimize missed leaks and false alarms over the long term [9,10]

iv Provide automatic dynamic retuning of the ***i*****EAF®** process models and/or **Water Detection** models when necessary to ensure sustained maximum savings, water detection performance and minimum false alarms over the long-term.

Conclusions

This paper describes Tenova's vision for Industry 4.0 as it applies to creation of an "Intelligent EAF" steelmaking process. This program is designed to provide continuous improvement and better technology/performance alignment between individual plants in companies with multiple production sites.

Tenova's Industry 4.0 Intelligent EAF solution incorporates several steps:

- Development & installation of a suite of robust, & reliable sensors that provide process data measurements in EAF critical areas including off-gas full spectrum analysis, off-gas flow, off- gas temperature & EAF static pressure

- Replacing statistical process models which are prone to excessive drift with a new generation of more fundamental thermodynamic & kinetic based process control models that incorporate real-time mass & energy balances

- Creating a digitalized interface that links process equipment, sensors, Level 1 & 2 networks, and process control models

- Using cloud computing services to store and analyze large amounts of process data from multiple EAF's & production sites

- Employing a team of highly trained process experts & data scientists applying machine learning techniques to develop improved & optimized 2nd & 3rd generation process control models

- Continuously monitoring model performance

- Providing automatic dynamic retuning of the models when necessary to ensure sustained maximum performance over the long-term

Figure 8: Tenova’s Digitalization Program Continuously Monitors System Hardware Health, Example of a NextGen® Dashboard

Figure 9: Tenova’s Digitalization Program Continuously Monitors System Software, Example Water Detection Dashboard

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