48º Seminário de Aciaria, Fundição e Metalurgia de Não-Ferrosos
Anais do Seminário de Aciaria, Fundição e Metalurgia de Não-Ferrosos ISSN 2594-5300 vol. 48, num. 1 (2017)

LATEST RESULTS IN EAF OPTIMIZATION OF SCRAP-BASED MELTING PROCESS: Q-MELT INSTALLATION IN KROMAN CELIK *

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Abstract

Competitiveness in Electric Arc Furnace production is pushing steelmakers to increase the throughput at the lowest expenditure. The technological challenge is therefore to operate the existing facilities at their top capabilities and to exploit materials and energy sources at the upmost yield and efficiency. Moreover, seizing the opportunity offered from the price variability of metallic feedstock calls for flexible practices, versatile equipment and tools to rapidly tune the melting profiles without hindering steel quality and equipment lifetime. The innovative Danieli Q-MELT Automatic EAF system addresses these aspects implementing a centralized control system which interacts with multiple technological packages. Each of these cutting-edge technologies focuses on one aspect of the EAF cycle, increasing machine availability and resource efficiency, by means of electrode regulation and foamy slag control, charging optimization, off-gas analysis and closed loop injectors control. Moreover, these modules provide the process supervisor application (Melt Model) with important information regarding the process status, thus allowing the adoption of a unified control strategy. The supervisor implements a robust statistical approach to identify process deviations in real time. The first results and technology perspectives inferred from the field immediately after the start-up are described in this paper.

Keywords: EAF, Gas Analysis, Post-combustion, Process Control, Yield, Sidewall Injection.

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1 INTRODUCTION

In today's highly competitive market situation, it is of outmost importance for EAF steel makers to optimize their processes in order to reduce operating costs and to improve safety and reliability of the equipment.
A common trend observed during the last five years is a generalized reduction in oxygen and fuel utilization, mostly driven by a worse quality charge mix and a lower productivity level requirement from saturated markets.
The comprehensive study on the chemical energy efficiency in EAF practice reported in their paper by Patrizio and Pesamosca [1] is clarifying the theoretical background explaining the observed tendency. Whenever the charge mix is poor in carbon and other oxidizing elements (silicon, manganese, chromium) the overall energy efficiency of oxygen drops down and turns into expensive yield losses.
Coal energy input is lower, compared to gaseous fuel burners. Intensive oxygen practices lead therefore to overall higher heat losses to the fumes treatment plant, incomplete CO combustion, iron oxidation and poor slag quality.
The current market situation is mostly driven by price competition. Volumes have kept shrinking in the recent period, especially in the steel commodities and in countries with mature economies.
Operating expenditure is the most important performance steelmakers are taking care of. Existing steel production over capacity is not pushing for higher production levels, while high quality commercial bar feedstock is widely available at competitive prices, mainly imported from Far East. Scrap prices are volatile and highly variable on short period. Low bulk density feedstocks and local market are cheaper and preferred to expensive imported or shredded feedstocks.
The question is therefore how to rapidly adapt to this highly dynamic market environment still holding competitive performances to keep proper profit margins.

Figure 1. Kroman Celik EAF

The solution calls for a highly automated EAF, equipped with efficient specialized equipment, advanced monitoring and sensing systems and adaptive integrated process control.
In July 2016 Kroman Celik, located in Gebze (Turkey), a producer of reinforcing bars and wire rods, choose DANIELI Q-Melt process control and MORE chemical package to upgrade their 150 ton EAF, figure 1, targeting to improve the EAF productivity and to reduce operative expenditures.

2 KROMAN CELIK EAF REVAMP

The main electric arc furnace design features are reported in the following table 1.

Table 1. Kroman EAF design features

Start up (year)	2010	
Power supply type	AC	
EAF Supplier	DANIELI	
EAF Type	EBT	
Tapped steel weight	150	t
Hot heel weight	25	t
Productivity	175	t/h
Annual Production	1.300.000	tpy
Inner panel diameter	7200	mm
Electrode diameter	710	mm
Pitch circle diameter	1350	mm
Transformer nominal rating	140	MVA
Max secondary voltage	1350	V

Since its start-up in 2010 the performances of the furnace have been outstanding, with a very fast learning curve [2].
More recently the progressive deterioration of the scrap bulk density and quality, called for a reduction in the oxygen use. Specific electric energy consumption increased and productivity dropped, mostly affected by the longer power-off time required by loading as many as 4 buckets of scrap.
Due to the above items it was decided to equip the meltshop with the Q-MELT Dynamic Heat Suite package, which is collecting all the melting information to perform automatic and dynamic adjustments during melting and specifically to perform the metallurgical control of the electric arc furnace process.
The system integrates Q-REG, the most advanced release of the dynamic electrode regulation with foamy slag control, taking advantage from coal and lime injection for keeping the arcs shielded and balanced at the highest power input, although not entailing excessive radiation losses.
Real-time process optimization and control is based on Lindarc^{TM}, a innovative fast gas analyzer performing in-situ laser spectrometry and a closed loop control post-combustion [3].
The chemical package has been revamped with the most recent MORE’s technologies for managing technological gases and solids’ injection [4]: M-ONE sidewall injectors to improve the oxygen and coal efficiency and Limejets to integrate also lime and dolomite injection to control and optimize the slag foaming practice.

3 ADAPTIVE PROCESS CONTROL: Q-MELT

A dedicated process supervisor was developed to apply a data-driven strategy to the electric arc furnace control. The application (Melt Model) implements a statistical approach to identify process deviations in real time. Process data are collected, clustered and filtered, extracting the average and deviation trends of the key process variables [10]. Such process fingerprint represents the expected process behavior of the heat. Comparing the real-time to the expected trend, the system performs an adaptive process control and acts on specific actuators (figure 2).

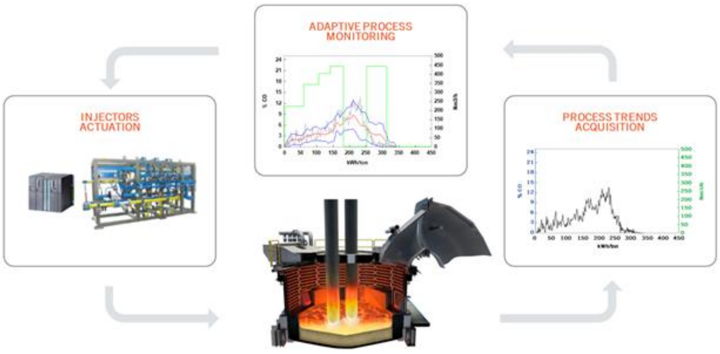

Figure 2. Melt Model implementation of a trend-based adaptive process control.

Melt Model applies this approach to control the decarburization process. At the start of the heat, the fingerprint of the key process variables (off-gas %CO, %CO2, %H2O, Total O2 and C flows, among others) is retrieved from the historical data base, selecting the information by means of the most relevant filtering criteria. This fingerprint represents the reference behavior of the heat. By comparing those expected trends with their real-time counterparts, the application detects whether the decarburization process is proceeding with the expected rate or requires adjustments. The soft landing controller thus adjusts the oxygen injection to hit the final carbon and temperature without over-oxidizing the heat (figure 3).

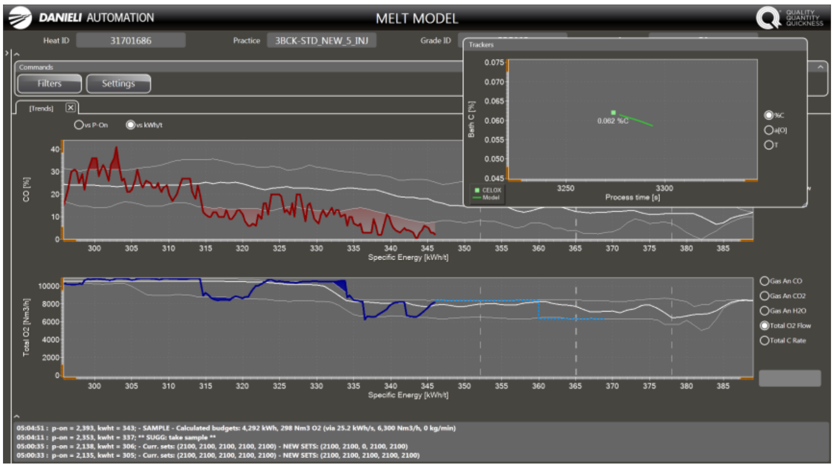

Figure 3. Melt model in action

From the first valid sample measurement on, the application also tracks the bath %C / Temperature / a[O] thanks to its integrated process models (figure 4). These models are fitted on the data stored by the system, so their output is tuned on the specific EAF considered and it adapts to slow process changes over time.

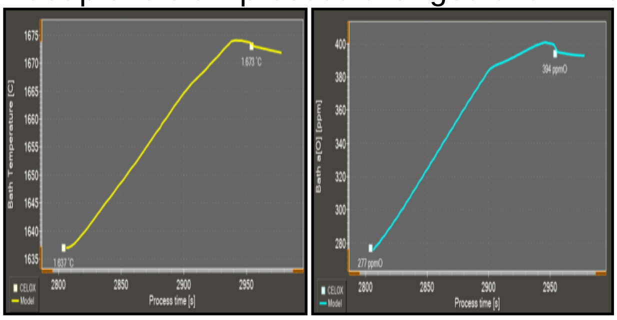

Figure 4. Melt Model decarburization tracking

The cartridge measurements results, as well as the steel analysis, are also considered by the application to control the decarburization: when available, this information is used to further increase the accuracy of the final bath composition and temperature.

4 Q-REG Electrode Regulator

Q-REG is DANIELI's most recent version of the arc control, integrating dynamic foamy slag regulation and electrical set point optimization (figure 5).
Accurate electrodes' positioning performances were further improved by means of a faster hydraulic response integrated with stiffer mechanical design. Several predictive maintenance diagnostic functions were added to prevent accidental component breakdown, keeping the system efficient along time.
The controller dynamically adjusts the electrical set-points to run consistently the furnace, adapting to the network conditions and achieving the highest active power input.

Figure 5. Q-REG overview

An innovative real-time irradiance supervisor (Q-RAY) evaluates the total irradiative heat flux along the furnace walls to modify the control targets in order to balance the thermal loads on the water-cooled panels (figure 6). It monitors the heat flux to the panels and integrates this information with the arc radiation calculated from the real time electrical variables. The goal of this controller is to keep the highest active power until the end of the heat, without severe stresses to the panels and the refractory lining in case of uncovered arc operation.
The main characteristics of the Q-RAY installed in Kroman Celik are:

- Possibility to unbalance dynamically the electrode current if the temperature of the corresponding panel reaches the alarm threshold.
- Possibility to reduce the tap position if the estimation of the temperature panel moves towards the trip threshold.

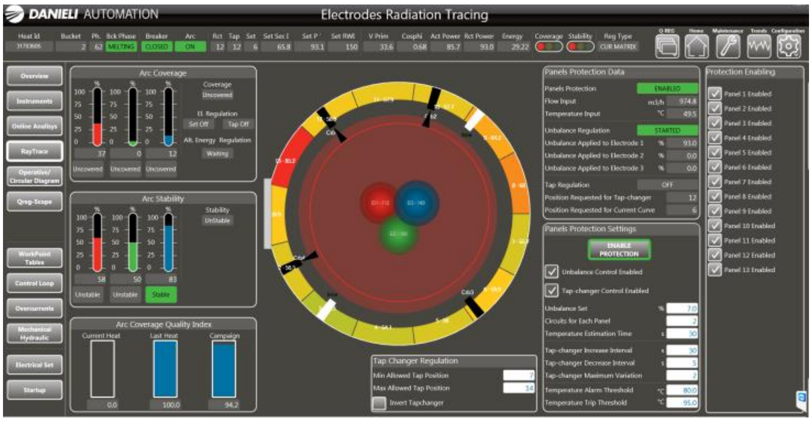

Figure 6. Q-RAY Electrodes Radiation Tracing

These features were enabled to improve the protection of the panels and at the same time it was possible to reduce by 5% the current on each electrode.
In addition to this, a tap holding strategy was adopted in order to keep as long as possible during the bucket melting the maximum tap adopted in the static profile (figure 7)

Figure 7. Tap holding strategy considering panels thermal load

4.1 Dynamic Foamy Slag Control

During the refining phase, arc coverage by the foamy slag plays a key role. The dynamic foamy slag control continuously monitors the slag conditions, evaluating the Arc Coverage Index (ACI), a proprietary function based on arcs voltage & current fast signal processing in real time.

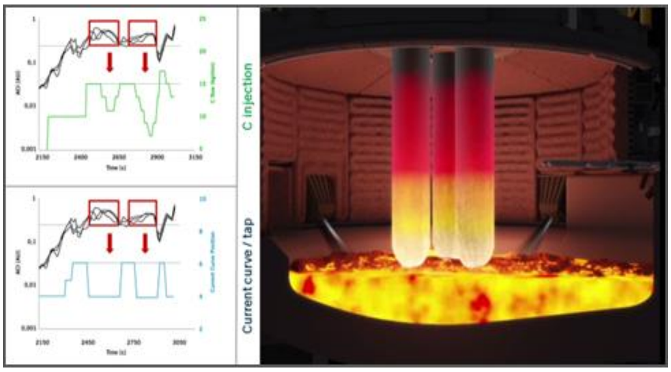

Figure 8. Dynamic foamy slag control

* *Technical contribution to the 48º Seminário de Aciaria, part of the ABM Week, October 2nd-6th, 2017, São Paulo, SP, Brazil.*

The status and tendency of the ACI are assessed by a controller acting on coal injection flow to adopt optimal arc impedances and increase the power heat transfer, while keeping the arcs shielded by the foaming slag (figure 8).
The ACI value is evaluated for each electrode individually and the coal injection is regulated by acting on the injector(s) closer to each arc.
Towards the end of the heat, dynamic regulation is applied also to lime-dolomite injection, to recover the proper slag basicity.

5. THE NEW CHEMICAL PACKAGE

The new EAF layout is reported in figure 9.
It is composed of:

- n.4 M-ONE combined oxygen and carbon injectors (to replace supersonic oxygen injectors and carbon lances);
- n.2 post-combustors;
- n.1 Oxygen jet at the sump;
- n.2 LIMEJET injectors for pneumatic delivery of lime and dolomite;
- n. 3 MOLI lime dispensers to dose and inject lime and dolomite into the EAF;

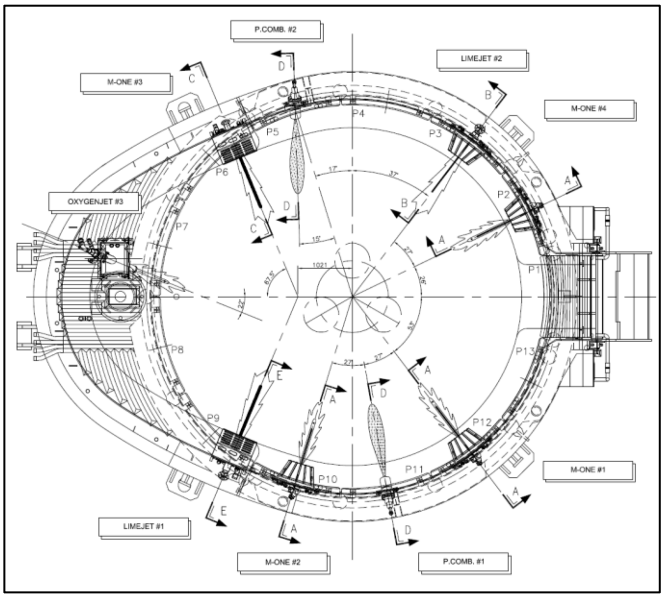

Figure 9. New EAF layout

The rationale behind the new layout concept is to concentrate the heat input in the cold spots of the furnace and to locate the lime and dolomite injection at the arc hot spots.
Post-combustors are installed at the cold spots, too. They are intended to cooperate with the sidewall injectors, in particular with M-ONE units, which can be considered as sources of carbon monoxide. Post-combustors are designed to blow soft oxygen in order to accomplish the carbon monoxide combustion inside the furnace close to the bath and inside the scrap during melting. The gas utilities were rerouted from the existing valve stands in order to limit the capital investment.

5.1. M-ONE injectors

M-ONE is integrating three functions in a single unit:

- Mixed swirled flame burner;
- High efficiency supersonic coherent oxygen lancing;
- High momentum coal injection.

The all-in-one design (figure 10) was initially developed with the target to reduce the number of tools installed in the furnace shell, in order to ease the assembly work, to reduce the capital investment and to improve the reliability of equipment.

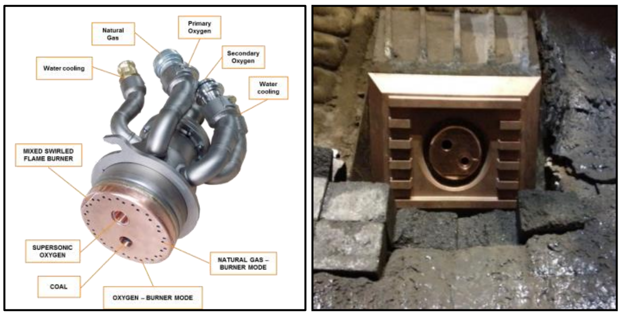

Figure 10. M-ONE injector and box installation

The powerful mixed swirled flame, spreading on a larger area is improving the burner efficiency, involving larger portions of scrap and having a reliable self-cleaning effect against tip clogging, not requiring any low oxy-fuel flame to prevent the slag sticking and skull formation (figure 11).

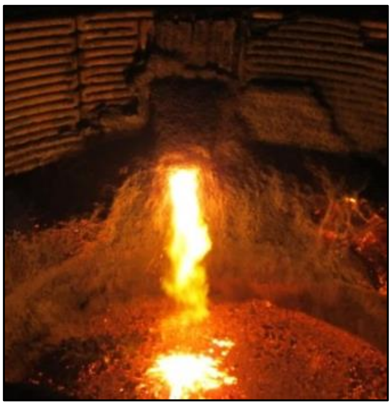

Figure 11. M-ONE injector: burner mode flame

Oxygen lancing is therefore more effective, adding to the advanced design of the De Laval nozzle rapid scrap meltdown and early access to the melt.
Combined coal and oxygen injection promotes immediate control of the liquid slag's interaction with refractories at the slag line. In the past, the distance between the oxygen and the coal injection points required time to complete the reduction reactions and FeO infiltration in the refractory wall was rapidly spoiling the bricks' matrix from the carbonaceous binder at the slag line.

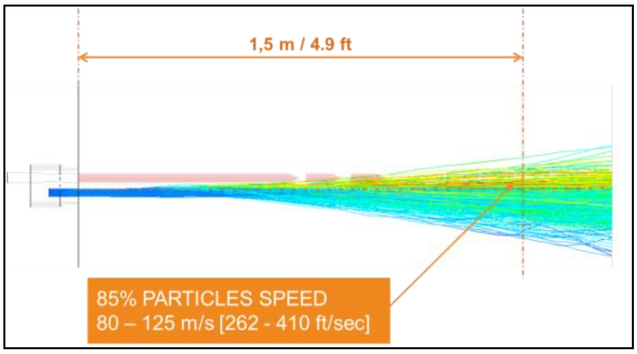

Figure 12. M-ONE injector: coal particle acceleration

Engineers took advantage from the proximity between the oxygen and the coal jets to accelerate the solids' particles by the faster oxygen gas stream. Extensive CFD parametric modeling was performed in order to maximize the acceleration of the solid particles by the jet's entrainment effect, although not wasting the supersonic oxygen free-jet structure, figure 12.

5.2. Lime and dolomite injection

Lime injection consists of a fully automatic system composed by a dry day bin for storing grain sized materials, accurately dosed by weighted pressure vessels, conveying solids pneumatically to dedicated sidewall injectors. Limejet injectors are tools specifically designed for injecting grain sized slag formers at a velocity of 60 to 80 m/s, sufficiently high to reliably penetrate the thick slag layer and disperse even the finer particles of flux at a distance in excess of 1.5 m (figure 13).

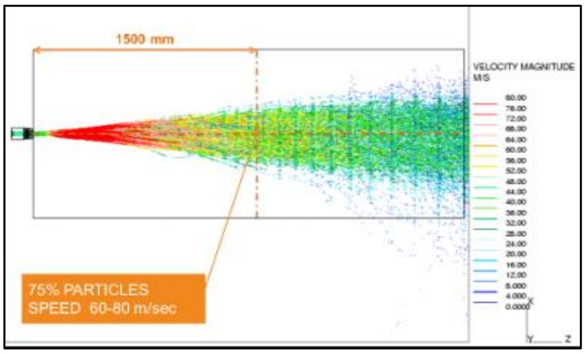

Figure 13. Lime particles' jet

Sidewall injection is set close to the slag: the short travelling path limits fines' loss to off gas. Consumptions savings and less dust load to the baghouse are direct benefits of the high material recovery.
System response time and slag reactions kinetics are very fast making the lime and dolomite injection suitable for dynamic control and integration with the electrodes' regulator.

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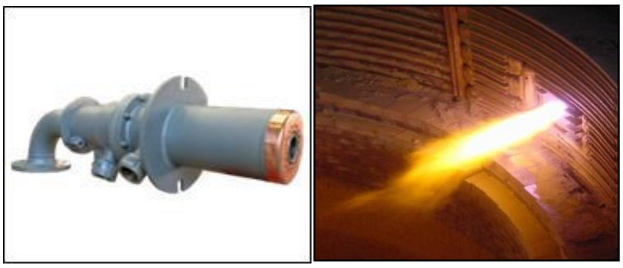

Figure 14. Limejet Sidewall Injector

The limejet injector integrates a powerful burner function in the same tip (figure 14). The flame is operated for heating and melting the scrap in front of it, preparing a cave in the metallic charge and preventing the formation of skulls at the wall, commonly suffered in conventional simple pipe installations, which are often prone to severe clogging.

Injection is integrated in the melting program and automatically controlled. It consistently runs the burner and adds the slag formers at the right melting phase by a desired flow rate.

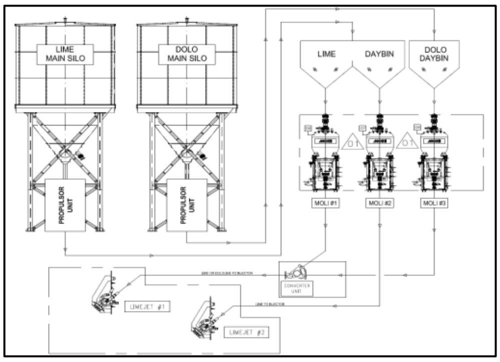

Figure 15. Slag Former injection system in Kroman Celik

Regulation of the correct feed rate accomplishes the required amount in convenient process time, without giving rise to accumulation of unreacted lime at the wall. The system therefore provides for the control of the slag V-ratio and local slag temperature.

In the solution adopted by Kroman Celik (figure 15), the ability to load also magnesia binders, allows for the slag double saturation. A MgO-FeO saturated slag promotes refractory savings (longer campaigns) and slag apparent viscosity, improving foamy slag [5]. These functions are especially valuable during superheating, when slag foam tends to decline as a direct consequence of FeO concentration and the viscosity drop that is following the temperature raise [6, 7, 8, 9].

6. LINDARC^{TM} GAS ANALYZER AND POST-COMBUSTION

LINDARC is a real-time off-gas analyzer, directly performing the measurement in the EAF's gas stream, based on the Tunable Diode Laser Absorption Spectroscopic (TDLAS) technique [3, 10].

It is able to continuously measure the off-gas composition and the temperature of the fumes crossed by the laser light source, figure 16.

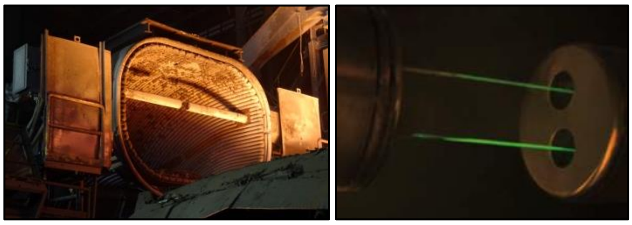

Figure 16. LINDARC installation and laser beams.

The measurement ranges for the species monitored are reported in the data sheet of table 2. A complete analysis is performed in a cycle time of 2 seconds.

Table 2. Lindarc^{TM} system features

Molecule	Range	Temperature
O_2	0 ÷ 25%	0 ÷ 1600 °C
CO	0 ÷ 100%	400 ÷ 1600 °C
CO_2	0 ÷ 100%	400 ÷ 1600 °C
H_2O	0 ÷ 50%	600 ÷ 1600 °C
Temperature		400 ÷ 1600 °C
Response Time		2 s

Conventional extractive systems require gas sample suction, filtering, cooling and conditioning before sending it to multiple gas analyzers. As a constitutive consequence they are slow and 20-30 seconds delayed behind the process. Gas' sample extraction and manipulation introduce intensive maintenance: extractive systems are prone to clogging, water condensation and air infiltration. This is sometimes impairing the analysis information issued to the process control and limiting the feedback control actions.

6.1 Lindarc^{TM} Installation

For practical reasons, the Lindarc^{TM} is installed downstream to the furnace. Between the roof elbow and the movable sleeve a gap is intentionally left open, entraining enough air to supply combustion oxygen and to cool down the fumes below 850°C at the settling chamber.
Air infiltrates and mixes, progressively reacting with the gas stream emerging from the furnace. The measurement path is placed to ensure that the laser beams interact only with the EAF off-gas, avoiding any dilution effect with the secondary air from the gap. The correct location of the beams is just right in the core of the EAF gas stream. It has been selected with the support of specific CFD simulations (figure 17) considering melting and refining operating conditions.

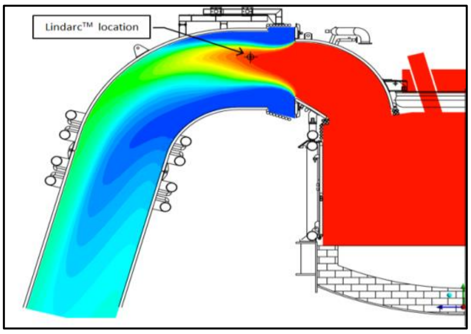

Figure 17. Gas-dynamics to select Lindarc^{TM} place

Two water cooled lances serve for the purpose. They protrude inside the fixed duct through the water-cooled walls, just downstream the movable sleeve.
These fingers (figure 18) shield the laser beam to reach the un-contaminated core of the hot off-gas stream.
At one side the transmitter units are installed. They beam the laser light through pipe channels flushed by nitrogen, a non-absorbing inert gas. At the lance exit, the laser beams cross the gas stream that selectively absorbs the spectra lines corresponding to specific molecules' resonance. The residual laser light reaches the receiver unit at the opposite side of the other lance.

Figure 18. Lindarc^{TM} receiver and control cabinet

The laser transmitter and receiver units are located in-line with the water cooled fingers, right outside the duct and are protected by heavy duty housings (figure 18) to prevent any damage, due to the very harsh environment typical of this location. The cooling system and purging gases are managed by a dedicated cabinet, located in a safe location away from the EAF, easy to access to.

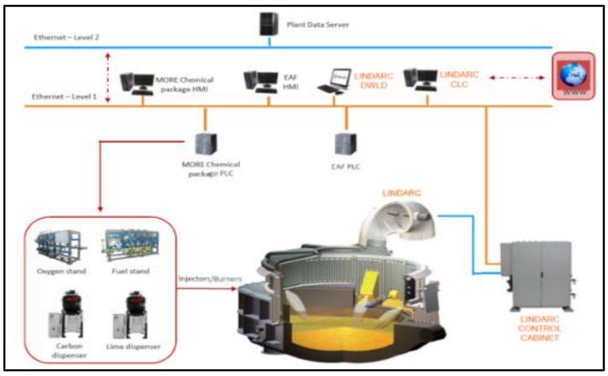

Figure 19. Lindarc^{TM} automation network

6.2 Lindarc^{TM} automation network

In order to store and manage the data provided by the LINDARC™ to be used in the dynamic process control logic, the system is connected to several devices (figure 19). The automation network includes the LINDARC™ Control Computer (LCC) with dedicated Human Machine Interface (figure 20), Closed Loop Control (CLC) and Dynamic Water Leak Detection (DLWD) software. Off-gas composition data are stored into a powerful database infrastructure (3Q Intelligence^{TM}) together with synchronous information retrieved from the whole EAF automation system. In depth historical process data analysis can be carried out locally or on remote computers via Internet or Intranet connections.

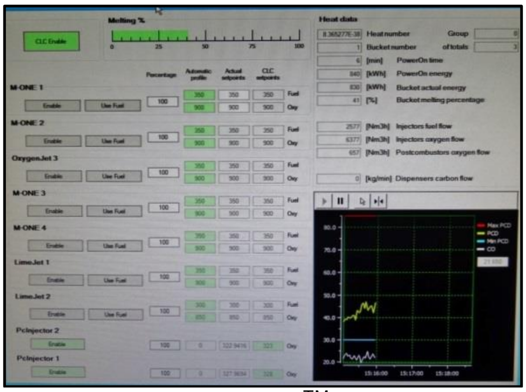

Figure 20. Lindarc^{TM} CLC HMI

6.3 Dynamic post-combustion control

Before the advent of the off-gas measuring technologies, the only way to perform post-combustion was to add some extra oxygen to the stoichiometric value via burners, based on pure prediction. Even if this practice was, and still is, widely diffused among steelmakers, it negatively impacts on electrode, carbon and oxygen consumptions as well is spoiling metallic yield.
Static input of extra oxygen cannot be efficient because CO and hydrocarbon evolution in the EAF freeboard are all but steady values [3]. They are indeed highly variable and hardly predictable from the melting program and the charge recipe.
The LINDARC™ technology provides an effective answer to this need. It performs a reliable and fast-response gas composition measurement and, via an algorithm named Closed Loop Control (CLC), it is able to transform this information into targeted feedbacks acting on dedicated post-combustor units (figure 21).

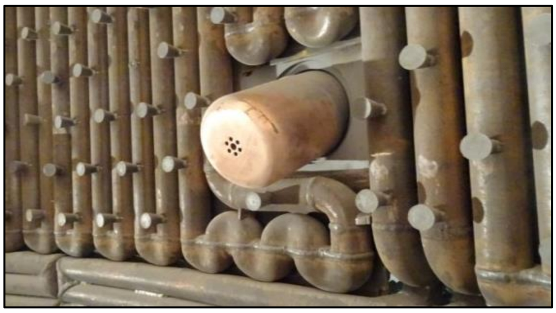

Figure 21. Postcombustor unit

During melting it is able to adjust the burners' oxygen/natural gas ratio, too, by following the real time furnace atmosphere oxidation level.
A key factor of this dynamic control is the very fast response time ensured by the LINDARC™ technology.
A specific algorithm has been developed to translate the information provided by the TDLAS technology into proper injection set points for the post combustion oxygen. The driving force used by the algorithm is the so-called Post Combustion Degree (PCD), which is defined as:

$$PCD = \frac{CO_2}{CO_2 + CO} \qquad (2)$$

that is used to assess the oxidation level at the furnace freeboard.
The lower the PCD, the higher extra-oxygen will be input by post-combustor units. The higher the PCD, the lower the burners oxygen-natural gas ratio will be, with the lowest limit defined by the oxygen-natural gas ratio set in the burner profile. Each individual unit (post-combustor, burner and sidewall injector) is independently configured, introducing specific limits for the flow rates and timing within the dedicated HMI application.

7. RESULTS

The EAF retrofit in Kroman Celik has completed in 9 days only and the first heat was performed on March 9, 2017, figure 22.

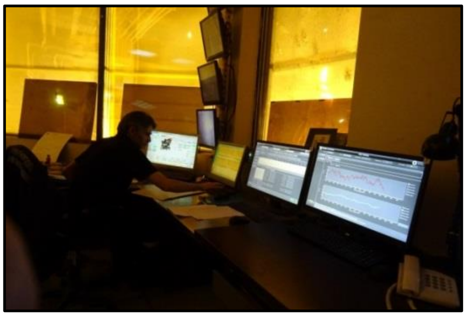

Figure 22. Control room with Q-Melt in operation

The learning curve was fast with a steep productivity ramp-up.
The first results achieved after few weeks of operation are quite interesting as reported in table 3.

Table 3. Achieved results

Power-on	min	-1
Tap-to-Tap	min	-2.4
Electric Energy	kWh/t	-25
Oxygen	Nm^3/t	+1.5
Natural gas	Nm^3/t	+0.3
Coal	kg/t	-3.8
Lime+Dolomite	kg/t	-0.7

The process fine tuning continued during the following period. The comparison between the 3 months after the startup (1602 heats) and the 6 months before the start-up (2867 heats) shows even more consistent performance gains (table 4).

Table 4. Achieved results after 3 months from startup

Power-on	min	-2.7
Tap-to-Tap	min	-2.7
Electric Energy	kWh/t	-20
Oxygen	Nm^3/t	+2.6
Natural gas	Nm^3/t	+0.7
Coal	kg/t	-1.0
Pig iron	%	-5
Lime	kg/t	-3.6
Dolomite	kg/t	-1.8
Electrode	kg/t	-0.3

The coal consumption was decreased by 1 kg/tls, but if we consider carbon input from pig iron the total carbon benefit could be extended up to 3.2 kg/tls; as additional benefit there was the possibility to cut the pig iron cost from the charge.
Despite the increase of oxygen input and the decrease of carbon input the steel oxidation was not affected due to the following reasons.

- The extra oxygen was given mainly in the post combustion phase during the bucket melting
- The carbon reduction was reduced thanks to the more effective side wall injectors and to the injection reduction in conditions of arc covered
- The oxygen dynamic control during flat bath operation allowed to control the level of oxidation within the established target

The main result achieved was the electrical energy reduction of 20 kWh/t, but if we consider the changes in the chemical input the total energetic saving was of 42 kWh/t, that brought to an increase of the energetic yield, intended as ratio between steel enthalpy and total energy input by 3%.

The comparison between the slag chemistry of the 2 months before startup and the 2 months after startup shows a higher level of repeatability of the process which leads to a lower value of slag parameters standard deviation (table 5):

Table 5. Standard Deviation reduction

		STDEV reduction
Fe2O3	%	-16.2
V-ratio	%	-12.6
MgO	%	-51.7

These values are also connected to an additional benefit in terms of shell duration, which was extended by 17% with respect to the previous data. As a matter of fact, the thickness of the bricks was sufficiently good to suppose a further increase of the shell refractory life in the next campaigns.

8. CONCLUSIONS

The results achieved are only the first step of the continuous improvement development plan agreed between Kroman, DANIELI and MORE.
The equipment described in the paper represents a complete suite of tools to manage and control the furnace with a full automatic approach.
The Q-MELT architecture is conceived to accumulate the process operating knowledge along time and to recognize variations by tracking the key performance indicators. It detects changes in process conditions and self-adapts by selecting the best practices to keep the production performances at the optimal level.

Acknowledgments

The authors would like to thank Kroman Celik A.S. personnel and management for the support given during the project execution and commissioning.

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