The Route to Combustion Technology for the Decarbonization Age

by **Alessandro Della Rocca**

Steel industry has set ambitious goals of reducing its greenhouse gas emissions in a relatively short time frame. To reach their targets, the iron and steel producers need a paradigm shift to fulfil environmental regulations and to evolve their processes towards low-carbon footprint technologies without losing competitiveness or profitability. To this end, both steel production stages, Upstream (up to liquid steel) and Downstream (from liquid to solid steel), need to implement an evolution or replacement of standard technologies.

More than 40 % of European steel comes from scrap recycling with direct carbon emission intensity of about 150 kgCO2e/ton for the Upstream portion. In this case, reheating and heat treatment processes in Downstream with direct emissions of 50-200 kgCO2/ton cover a relevant fraction of total direct carbon intensity of steel products. Consequently, the decarbonization of the steel recycling route must take into account low-carbon heating solutions. In this energy transition scenario, Tenova proposes a stepwise approach to the decarbonization of heating furnaces. After a first step of efficiency optimization, direct or indirect electrification is pursued as much as possible to minimize the energy consumption. This is possible only up to a critical temperature, where other process constraints (scale formation, heating efficiency, production flexibility) come into play. Hydrogen and non-fossil fuels combustion are thus required for the final heating range at high temperature, also because they provide a protective atmosphere against surface oxidation.

Since 2019, Tenova is developing novel combustion technologies to reduce the carbon emission intensity by using green hydrogen and low-carbon fuel mixtures. Tenova HydrogenReady combustion technology and allows full fuel flexibility (from 0 % up to 100 % of hydrogen enrichment in traditional fossil fuels) by overcoming the typical limitations of hydrogen combustion in terms of flame stability and NOx emissions. Tenova Smart Burner platform implements digital solutions on each single burner able to optimize operation and maintenance activities on high-efficiency combustion systems, such as self-recuperative and regenerative burners. Since a key challenge for the metal sector is the so-called 'valley of death' between R&D&I activities and the first industrial deployment, some examples of applications of the Tenova HydrogenReady technology will be presented to elucidate the main strategies for an industrial use of flexible hydrogen firing.

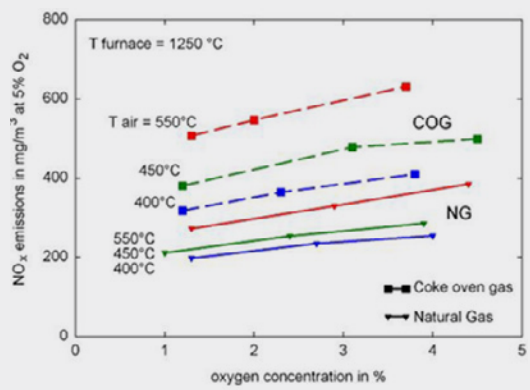

Fig. 1: Comparison of NOx emissions for the same furnace equipped with natural gas and COG combustion systems at different air preheating temperatures. (Source: Tenova Italimpianti)

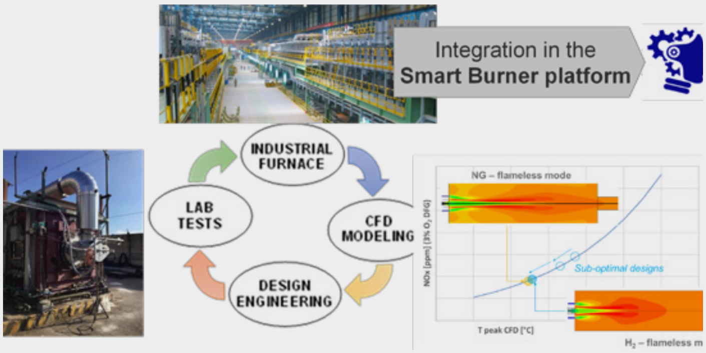

Fig. 2: Tenova standard approach for burner development/improvement cycle. (Source: Tenova Italimpianti)

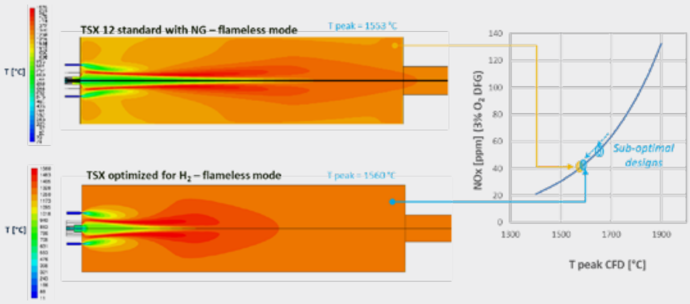

Fig. 3: Temperature field in CFD simulations of 100 % natural gas and 100 % hydrogen firing regimes for Tenova TSX burner. Expected NOx emissions estimated from the temperature peak in CFD simulations predict almost the same amount of emissions at stack for 100 % natural gas and 100 % hydrogen firing modes. (Source: Tenova Italimpianti)

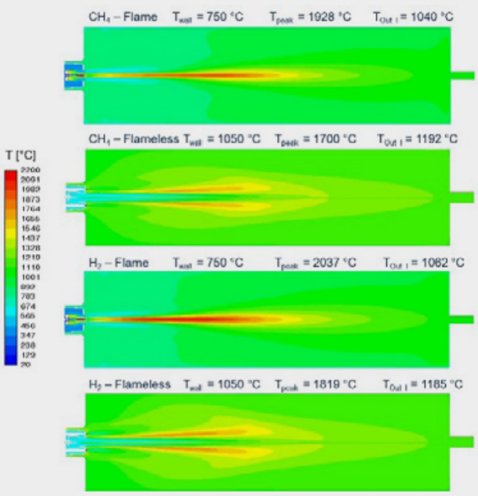

Fig. 4:. Temperature field in CFD simulations at different hydrogen enrichment percentages in natural gas for Tenova TRKSX burner. (Source: Tenova Italimpianti)

THE DEVELOPMENT OF TENOVA HYDROGENREADY BURNERS

Full hydrogen firing is a novel technique for reheating and heat treatment furnaces. Common experience in steel industry indicates that the increasing of combustion air temperature in high efficiency furnaces means a sensible increase of NOx emissions, especially in the case of fuel mixtures having high hydrogen content such as coke oven gas (COG).

The full replacement of methane by hydrogen will enhance the reactivity of the system further increasing NOx emissions. To overcome this issue, non-conventional combustion technologies such as flameless combustion represent an effective solution. The key aspect is the dilution of fuel and oxidizer streams with the exhaust gases. As a result, the local oxygen concentration in the reactants is substantially reduced. The result is a reaction zone characterized by diluted reactants, non-visible flame, and more uniform temperature leading to a strong reduction of NOx emissions.

Tenova has a long R&D tradition in leading edge combustion technology. Since early 2000s, Tenova R&D team developed an interdisciplinary design process including Computation Fluid Dynamics (CFD) modeling, industrial scale test and industrial applications. This consolidated workflow (**Fig. 2**) allowed to drastically reduce the time to market for the development of new hydrogen firing solutions: In particular, given the high cost and safety issues associated with on-site hydrogen storage, Tenova HydrogenReady technology was developed to burn variable mixtures of fossil backup fuels (i.e., natural gas, NG) and hydrogen (H_2) possibly up to 100 % H_2. In order to cover the full range of industrial furnaces two different burners were developed:

- Tenova TSX SmartBurner, flameless burners for side mounting in reheating furnaces.
- Tenova TRKSX SmartBurner, self-recuperative flameless burners for heat treatment furnaces.
- Tenova TRGX SmartBurner, regenerative flameless burners for reheating in continuous or batch furnaces.

Following the consolidated Tenova approach, each burner was first simulated via CFD modelling in order to refine its design and to align the system performance (flame length, NOx emission, temperature uniformity, air preheating efficiency) to the desired characteristics and project goals. All the simulations were carried out with EDC turbulence-chemistry coupling approach, DO radiation model and properly optimized kinetic mechanisms for capturing the effect of NG/H_2 combustion process.

PROTOTYPES DESIGN AND THE CFD SIMULATION APPROACH

The starting point of this development was the TSX burner family, previously adapted to COG firing with a commercial success. The goal was to develop a multi-fuel NG/H_2

flameless burner for high temperature reheating furnace applications able to keep NOx emissions well below the strictest envisioned limit (80 mg/Nm3 at 5 % of oxygen in dry flue gases) with combustion air temperature above 400 °C. A complete CFD optimization study was carried out for several alternative designs of the H_2 TSX prototype.

After an initial design review phase, an optimal burner geometry was identified that was able to maintain a constant temperature peak at any percentage of hydrogen content within the NG/H2 fuel mixture. For such specialized design, predicted NOx emissions are very close to the typical emissions of a standard Tenova TSX burner operated in natural gas firing mode (**Fig. 3**).

A similar CFD activity was carried out for the Tenova TRKSX burner. In this case, several designs were investigated in order to identify the best solution in terms of NOx emissions, flame stability and temperature uniformity within the furnace chamber. **Fig. 4** shows the results of the CFD simulations in terms of temperature field at different hydrogen enrichment levels. It is possible to notice that by increasing the hydrogen content in the fuel mixture, the reaction zone marked by the temperature peak region tends to shorten in proximity of the burner fuel nozzle thus becoming more intense. This is a result of the higher diffusivity of hydrogen with respect to methane and of the different self-ignition characteristics between the two fuel types.

LABORATORY TESTS

Following the standard Tenova R&D cycle, the TSX SmartBurner prototypes optimized through CFD simulations were manufactured and characterization tests were carried out at Centro Combustione Ambiente (CCA) with the aim to verify the design and performance (**Fig. 5**).

The TSX H2 flameless burner was tested in flame and flameless modes at 1250 °C furnace temperature with combustion air pre-heated at 450 °C. Several NG/H_2 fuel mixtures were tested by changing the amount of hydrogen content by 0 %, 20 %, 40 %, 60 %, 80 % and 100 % in volume.

The SmartBurner framework was adopted for the Tenova TSX H2 flameless burner and the IIoT equipment was tested during the experimental work at CCA. The burner was equipped with air and fuel flow rate sensors, pressure sensors, temperature sensors and accelerometers in order to extract values of several process quantities. Furthermore, a novel optical sensor developed by Tenova in the frame of the on-going "BURNER 4.0" RFCS project [16] for flameless process monitoring was fitted onto the burner body with the aim to test it in the hydrogen flameless combustion regime. The Tenova AlphaEdge IIoT unit collected data from low-frequency sensors (flow rate, pressure, temperature) and post-processed high-frequency data (vibrations and optical signals). Real time data, statistics and process diagnostics were collected by the TenovaEdge and safely stored into Tenova Cloud, as shown in **Fig. 6**. The Cloud applied further processing operations and elaborated KPIs and KHIs for the single burner unit, which were retrieved by several mobile devices by using the intuitive functionalities of the Tenova Wide dashboards.

The characterization campaign on the TRKSX burner required a new dedicated test furnace that was realized at Centro Combustione Ambiente (CCA) (**Fig. 7**). The different design alternatives identified from the CFD study were preliminary tested to define the final design of the

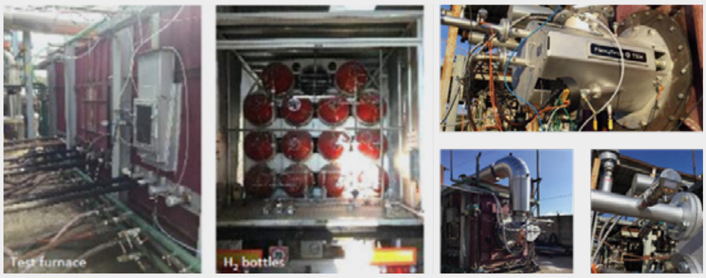

Fig. 5:. Tenova TSX flameless burner installation at CCA. (Source: Tenova Italimpianti)

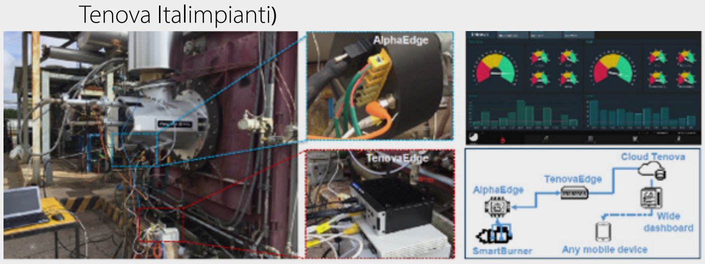

Fig. 6: Tenova SmartBurner infrastructure equipping the TSX H2 flameless burner at test furnace. (Source: Tenova Italimpianti)

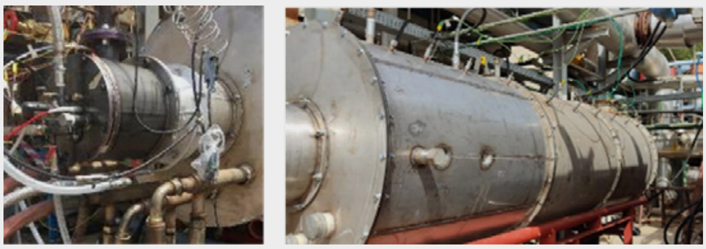

Fig. 7: Test furnace for Tenova TRKSX H2 flame/flameless burner at CCA. (Source: Tenova Italimpianti)

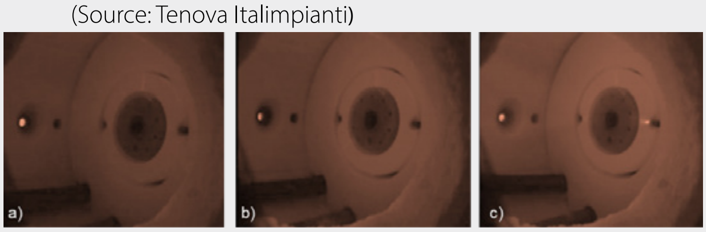

Fig. 8: Experimental tests of Tenova TRKSX in flameless mode: a) 100 % natural gas firing, b) 50 % natural gas and 50 % hydrogen firing and c) 100 % hydrogen firing modes. (Source: Tenova Italimpianti)

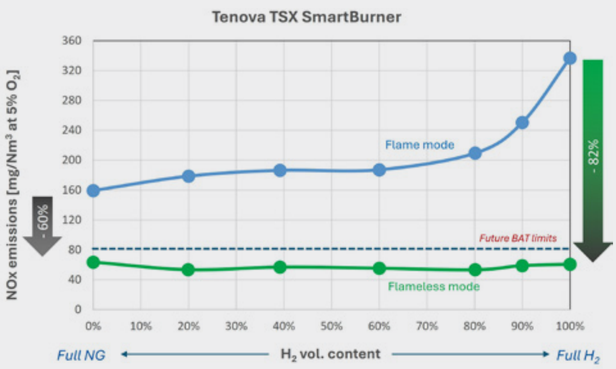

Fig. 9: Tenova TSX SmartBurner experimental results. In the flame regime, a relevant increase in NOx emissions is verified at hydrogen contents above 60 % while in optimal flameless regime the level of NOx emissions is always below 80 mg/Nm3. (Source: Tenova Italimpianti)

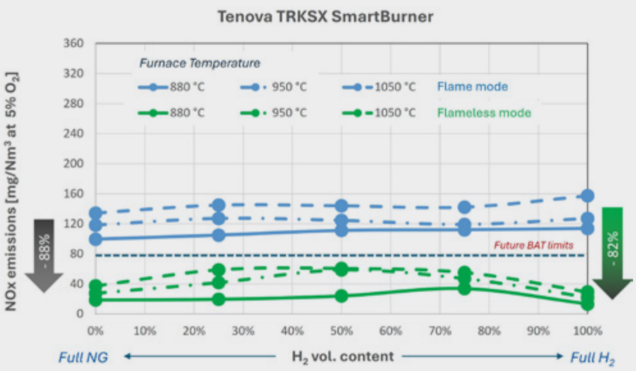

Fig. 10: Experimental results of normalized NOx emissions from Tenova TRKSX SmartBurner in flame and flameless modes at different furnace temperatures and at different hydrogen enrichment levels in natural gas. (Source: Tenova Italimpianti)

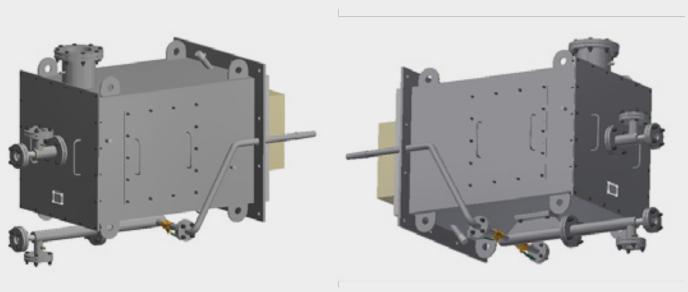

Fig. 11: Tenova TRGX HydrogenReady regenerative flameless burner. (Source: Tenova Italimpianti)

Tenova TRKSX burner. The best configuration was fully characterized. **Fig. 8** shows some infrared pictures of the burner behavior running in flameless mode with different hydrogen enrichment levels in the fuel mixture. It can be observed that flameless conditions are well established in the system at any hydrogen enrichment percentage.

Moreover, moving from full natural gas conditions (**Fig. 8a**) to full hydrogen (**Fig. 8c**), a small reactive zone appears in front of the flameless lance (right-side region of Figure 8c). This phenomenon is related to the higher reactivity and diffusivity of the hydrogen and confirms the CFD predictions (**Fig. 8**).

EXPERIMENTAL RESULTS

The characterization results of the 3 MW flameless burner for side mounting in reheating furnaces, Tenova TSX SmartBurner, are reported in **Fig. 8** in terms of normalized NOx emissions for both the flame and flameless regimes. When the burner is operated in flame mode, as is the case at furnace startup or whenever the process temperature is below the fuel self-ignition temperature, NOx emissions rise slightly (about 20 %) when passing from full natural gas firing to 20 % and 40 % of hydrogen enrichment, in agreement with the test performed by others [11].

The increase of NOx emissions up to 60 % of hydrogen content follows the behavior already verified in COG firing cases, (**Fig. 1**). As soon as the hydrogen content rises above 60 % vol., an exponential increase of NOx emissions is observed. In flame mode, the emissions at 100 % hydrogen firing are more than two times the amount of NOx produced in natural gas firing mode. This confirm the challenge of hydrogen utilization in the energy transition scenario of reheating and heat treatment furnaces: by lowering CO2 emissions with hydrogen enrichment, a sharp increase in NOx emissions is expected when using conventional combustion techniques.

In Tenova TSX H2 burner, this constraint is circumvented by working in flameless regime. As shown in **Fig. 9**, it is possible to maintain the low level of NOx emitted in natural gas firing mode across the whole range of NG/H2 fuel mixtures [17]. This occurs without any modification to the burner components, but as result of switching the gas injection from central lance to side lances. Thus, the NOx emissions levels of 60 mg/Nm^3 at 5 % of oxygen with air temperature at 450 °C and furnace chamber at 1250 °C, in flameless combustion regime with hydrogen firing is more than 80 % less with respect to typical hydrogen flames.

The characterization campaign of the 200 kW self-recuperative flameless burner for heat treatment furnaces, the Tenova TRKSX SmartBurner, also confirms the strong reduction of NOx emission in case of flameless operation, as visible from **Fig. 9**.

At the lower process temperature (880 °C) the NOx emissions peak is around 75 % vol. of hydrogen content in the fuel mixture, while at higher process temperatures (950 °C and 1050 °C) this peak is shifted towards lower hydrogen content (i. e. at 50 % hydrogen enrichment), as visible from **Fig. 9**. Nevertheless, at any furnace temperature and at any hydrogen content the NOx emissions remain well below the target emission limit of 80 mg/Nm³, thus confirming the suitability of hydrogen-ready Tenova SmartBurner combustion systems to the decarbonization of reheating and heat treatment furnaces.

OXYGEN-ENHANCED HYDROGENREADY REGENERATIVE BURNERS

Especially in the context of energy transition, the choice of a high-efficiency combustion systems becomes crucial because low-carbon fuel is generally more expensive than traditional fossil fuels, to this end, the adoption of regenerative burners can be particularly effective.

For this reason, Tenova expanded its regenerative burner solutions integrating a novel HydrogenReady technology able to fire oxygen-enriched air preheated to very high temperatures (> 1000 °C) by using high alumina ceramic honeycombs or ceramic spheres. The new Tenova TRGX HydrogenReady burners with oxy-enrichment are capable of operating with variable amounts of hydrogen in the fuel and oxygen in the combustion air. This extremely flexible operation fits perfectly with the use of water electrolysers that produce hydrogen and oxygen streams. The ability to use preheated oxygen at high temperature air which is enriched with oxygen for furthermore increasing efficiency maintaining at very low level the NOx emissions.

It is known that the higher flame temperature linked to the higher air preheating temperature produces a potentially higher quantity of NOx; this is increased by working with hydrogen, which produces a higher flame temperature than the natural gas one. The challenge is therefore to keep NOx emissions to a minimum level without reducing the preheating efficiency and the solution consists in the use of flameless combustion. For this reason, the burner couple is equipped with double gas inlet: the first working in flame mode at low temperature and the second in flameless above the self-ignition temperature of the furnace.

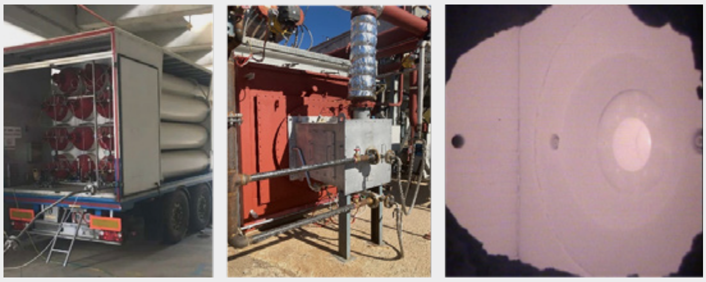

Fig. 12: Setup for the experimental tests of the Tenova TRGX HydrogenReady burner: hydrogen bottles on the truck trailer (left), test furnace (center) and the regenerative burner prototype firing 100 % hydrogen in flameless mode (right). (Source: Tenova Italimpianti)

The couple of burners (**Fig. 11**) is designed for a thermal power of 1 MW but the burners will be able to work up to 5 MW with different sizes. If the use of regenerative burners allows maximizing efficiency, it is known that also the enrichment of the combustion air with oxygen has an important impact on the reduction of gas consumption. Oxyfuel burners are in fact used to increase the productivity of a plant or to reduce the specific consumption of a plant fed with combustion air. Although the two technologies are usually in opposition, the burner is fed with air enriched with oxygen. The use of oxygen is very interesting when it is produced by electrolysis and in combination with the production of hydrogen; in this case, in fact, the cost of oxygen production is minimal considering the fact that the primary objective of an electrolyser is related to the production of hydrogen. For these reasons, it is therefore decided to test the regenerative burner with oxygen enrichment in the combustion air. Oxygen is therefore injected into the combustion air upstream of the regenerator and the

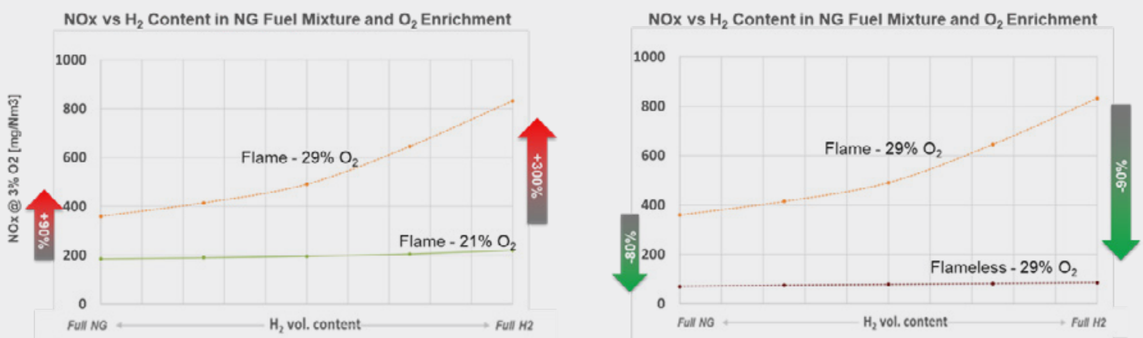

Fig. 13: NOx emissions of Tenova TRGX Hydrogen-Ready burner with 21 % and 29 % of oxygen in the preheated combustion air at furnace operating temperature of 1250 °C. (Source: Tenova Italimpianti)

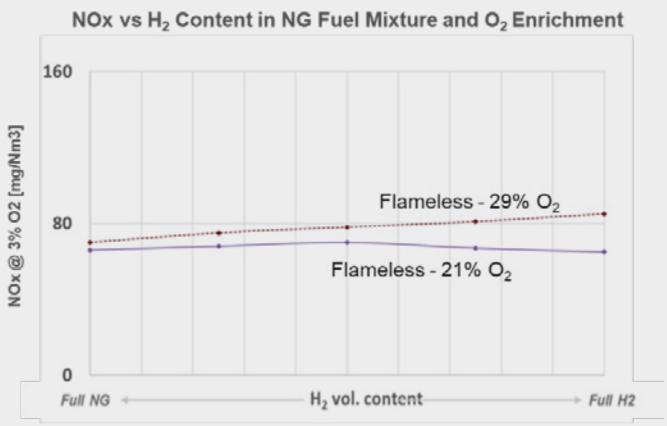

Fig. 14: NOx emissions of Tenova TRGX Hydrogen-Ready burner with 21 % and 29 % of oxygen in the combustion air in flameless mode at furnace operating temperature of 1250 °C. (Source: Tenova Italimpianti)

amount of oxygen used is limited to obtain an air-oxygen mixture of 29 % oxygen. The test furnace having an internal section of 2x2 m and an available length (wall-to-wall) of about 5 m is made of a steel casing with internal refractory and ceramic fiber linings. The burners are placed on the two frontal walls of the furnace, as shown in **Fig. 8**, while the waste gases outlet is placed at the middle of the furnace. The furnace is water-cooled by means of several movable water lances and it features 10 thermocouples placed at different axial positions and several optical inspection ports in order to monitor the flame appearance. The hydrogen was supplied from a truck trailer (**Fig. 12**) with eleven hydrogen bottles, while the natural gas was coming from the standard pipeline. In addition, a bottle pack is used to supply oxygen to combustion air for enriching it up to 29 %, limit for which it is not necessary to provide special piping suitable for combustion with pure oxygen.

During the tests, the burner behavior was changed according to different control parameters in order to map their effect on burner operation and performance. The tests were carried out over several test days during which the burner was cold ignited with natural gas and then fed with any type of H_2/NG mixture once the flame was ignited. When the furnace temperature reached 850 °C the burner was also operated in flameless mode in order to measure the NOx emissions.

The trend of NOx emissions in flameless combustion is almost flat, remaining constant for any percentage of hydrogen enrichment; the burners are able to produce very low level of nitrogen oxide – 70 mg/Nm^3 at 3 % oxygen at 1250 °C (as NO_2) and 55 mg/Nm^3 with furnace at 1150 °C. In flame mode, the higher flame temperature of the hydrogen combustion generates a higher concentration in NOx species. In particular, by increasing H_2 content in natural gas mixture, the nitrogen oxides emissions increase from 145 and 185 mg/Nm^3 (at 3 % O_2 and 0 % H_2) to 205 and 220 mg/Nm^3 with 100 % H_2, respectively at furnace temperatures of 1150 °C and 1250 °C.

During the experimental session, the burners were also fed with oxygen-enriched combustion air. In this case, a flow of oxygen is injected in the combustion air for reaching an amount of oxygen at 29 %. The higher value of oxygen in the air allows to reduce the percentage of nitrogen and to increase both the flame temperature and the heat flux to the charge due to the higher presence of water vapor and CO_2 (in the case of natural gas presence in the fuel mixture). This implies a reduction of fuel consumption, but the higher flame temperature produces high NOx emissions. As shown in **Fig. 13**, the trend was confirmed by experimental results where the burners reached more than 800 mg/Nm^3 of NOx in flame combustion when using 100 % hydrogen. By switching to the flameless mode, a significative reduction of the NOx emissions is possible, by bringing the values back to levels similar to those of flameless combustion with air (i. e., at 21 % oxygen content). In **Fig. 14**, the NOx emission curves produced by the flameless burners fed with air and with oxygen-enriched air at 29 % O_2 are reported, and the maximum value is about 85 mg/Nm^3 at 3 % of O_2 in dry flue gases.

IMPLEMENTING THE DIGITAL REVOLUTION IN INDUSTRIAL BURNERS

Optimization of modern combustion systems in steel reheating furnaces requires additional levels of information from the installed equipment. Complex combustion systems such as self-recuperative burners in free flame and radiant tube applications are particularly effective for curbing CO_2 emissions. The situation is even more complex in regenerative burners installations, where the combustion system behaviour is highly dynamical due to the continuous alternation of the regeneration phase (when burners suck flue gases from the furnace in order to preheat solid bed of regenerators) and the firing phase (when cold air is provided to the regenerators to be preheated at very high temperatures). Keeping the combustion equipment always in the optimal design condition requires additional efforts from the furnace operation and maintenance teams. This issue can be overcome if one provides embedded sensors in each burner units with the aim to collect relevant physical quantities and to extract trends of key performance indicators (KPIs, representative of the combustion performance) and key health indicators (KHIs, representative of the integrity of critical burner components). The first industrial installation of prototype SmartBurners

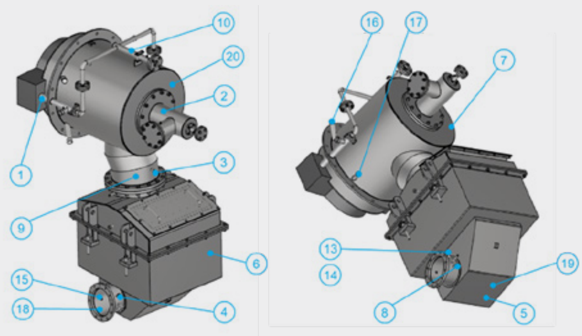

Fig. 15: Tenova TRGX 16 SmartBurner prototype: (1)-(7) temperature sensors, (8)-(10) pressure sensors, (13)-(15) chemical species sensors, (16) and (17) optical sensors, (18)-(20) mechanical sensors. (Source: Tenova Italimpianti)

Fig. 16: Oxygen measurements in two locations allows enhanced maintenance operations of the flue gas cycling valve. (Source: Tenova Italimpianti)

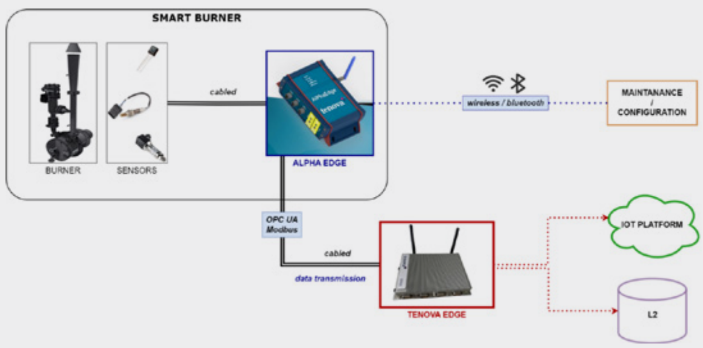

Fig. 17: SmartBurner industrial implementation as a combination of SmartBurners with data infrastructure elements combining the cloud-based solution (IoT platform) with the traditional automation control system (L2). (Source: Tenova Italimpianti)

was carried out in the rotary hearth furnace at Tenaris Dalmine during the long-term tests of the European research project 'BURNER 4.0' (This project has received funding from the Research Fund for Coal and Steel under grant agreement No. 847237). A couple of flameless regenerative burners with integrated sensors were tested against real furnace operation in order to better understand the real conditions of industrial burners in a highly dynamic furnace environment.

After initial troubleshooting due to the harsh operating conditions, the designs of the sensors and signal processing units were completely reviewed and refined. The architecture was integrated into the typical automation control system of industrial furnaces, in order to elaborate KPIs and KHIs during the tests. In particular, the direct measurement of the oxygen level in regenerated flue gases allowed highlighting potential issues in terms of the air and waste gases cycling valves. These findings allowed to directly take into account any possible mass flow imbalances into the control loop and allowed fine tuning of the air excess of regenerative combustion system.

The SmartBurner platform is physically implemented by using physical connections and Industrial IoT elements, as represented in **Fig. 17**. The sensors embedded in each SmartBurner are connected by cables to the local edge computing unit (AlphaEdge) which adds a digital layer to each industrial burner. In this way, each SmartBurner (i.e., AlphaEdge) unit can be accessed by wireless or Bluetooth to implement required maintenance operations or configurations (i. e., changing IP address after a network redesign, modifying the physical unit conversion function after the substitution of a pressure transmitter, etc). Each SmartBurner unit is then connected in Opc UA or Modbus protocol via Ethernet cable with PoE to the industrial PC that connects all the IoT units on field (Tenova Edge). The Tenova Edge unit also connects the L2 automation system, thus making possible to also leverage the signals from the furnace automation system for driving KPIs and KHIs and feeding the Digital Twin. At the same time, the Tenova Edge unit streams all these data (data from the SmartBurners and data from L2 system automation) to the cloud based IoT platform with the aim to enable process statistics, AI models and other post-processing operations requiring the existence of historical process database.

CONCLUSIONS

Energy transition trends push for the steel industry to start decarbonization as soon as possible. For steel producers on the scrap route, the energy transition scenario entails to cut down direct carbon dioxide emissions from reheating and heat treatment furnaces. In order to foster the decarbonization of industrial furnaces Tenova has started a transition process of its combustion system portfolio towards a 'hydrogen-ready' SmartBurner platform, where full hydrogen flexibility (from 0 % up to 100 % enrichment of traditional fossil fuels) is combined with advanced IIoT solutions for simplifying maintenance, tuning and commissioning of future-proof combustion systems.

The development of a full HydrogenReady burners portfolio powered by hydrogen can be defined as the state of the art of low environmental combustion technologies thanks to the high efficiency which reduces fuel consumption, operational expenditure and CO_2 emissions. To this end, the optimization of flameless technology minimizes NOx emissions and allows the use of increasing quantities of hydrogen which potentially eliminates CO_2 emissions. These motivations guided Tenova first developments in flexible hydrogen firing solutions that are now labeled as HydrogenReady.

The introduction of the oxygen enrichment of the preheated combustion air is a further step towards high efficiency combustion. Compared to a standard air regenerative burner, the presence of oxy-enriched air at 29 % O_2 reduces consumption by about 7 %, while compared to a burner with preheated air at 400 °C the reduction is about 20 %.

Self-recuperative and regenerative combustion systems emerge as the most promising for the energy transition scenario. By using embedded sensors and IoT edge computing approaches Tenova developed the SmartBurner platform for enhanced process control through Industry 4.0 solutions: In this way, complexity in maintenance operations for regenerative burners can be minimized in a cost effective way. The digital-enhanced process control techniques delivering real time key performance indicators in remote dashboards allow plant personnel to maintain stable performance of new combustion systems.

Tenova believes that the adoption of hydrogen as a fuel in hot rolling processes can be considered an industrial reality, where the HydrogenReady and SmartBurner solutions are able to offer efficient, clean and low-carbon solutions for the future combustion systems.

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