Hydrogen Burner in EAF: results from the development plan

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ABSTRACT

To speed up the decarbonization of the steelmaking process and granting a sustainable production, SMS Group, as partner of the European funded project: Developing and Enabling H_2 Burner Utilization to Produce Liquid Steel in EAF – DevH2forEAF, designed and tested its own multi-fuel-burner for EAF, capable to work with NG/H_2 up to 100% hydrogen. Starting from CFD simulations, testing small prototype burners first and then a 3 MW burner in a combustion chamber station, a 4 MW burner has been tested in production in an EAF. This paper presents the development, the challenges and the results obtained so far in various testing and operating conditions.

INTRODUCTION

The steel production trough electric arc furnaces (EAF) play an increasingly important role in modern steelworks concepts.[1] For example with 81 % in Italy and 61% in Spain, the production of EAF steel is significantly higher than steel production via the blast furnace/basic oxygen furnace route. In the modern EAF, the contribution of the chemical energy for the scrap melting and refining is the range of 25-45% of the total energy required. The Natural Gas (NG) burners provide in the range of 40-80 kWh/t of energy. This means that the production of 100 tons of steel requires the combustion of 370-750 Nm^3 of NG with CO_2 emission in the range of 0.75-1.5 tons. The substitution of just 10% of NG with hydrogen in the whole steel production will bring a remarkable reduction of CO_2 emissions.[2]

Within this frame, the DevH2forEAF project represents a step forward to independence from fossil fuel and bold action to furtherly cut CO_2 emissions in steel sectors. The DevH2forEAF project is carried out with support from the European Union's Research Fund for Coal and Steel (RFCS) research program (Grant Agreement Number 101034081) started in 2021, facing and solving several issues, with the main scope to prove that hydrogen use in EAF is possible and feasible.

SMS Group has designed and manufactured a new H_2 injector-burner able to work with all the NG/H_2 mixtures up to 100% hydrogen. The H_2 injector-burner has been designed and manufactured for working in severe environment, thus ensuring mechanical and thermal resistance in respect of EAF operative conditions.

To achieve the final target of full-scale testing in EAF production, a step-by-step approach has been implemented.

Simulations by means of CFD have been the starting point, with validation by means of small-scale prototypes of the flame appearance and the cooling effectiveness. Additional small-scale prototype has been used for metallurgical assessment in a pilot scale EAF (at RWTH-IoB in Aachen, Germany). Full scale unit has then been test and validated in a combustion chamber (at the RINA-CSM experimental station in Dalmine, Italy), before the industrial test in the EAF in Pittini Ferriere Nord (Italy) and later in Celsa Barcelona (Spain).

DISCUSSION

1. Design and construction of the H_2 injector-burner

SMS Group designed the H_2 injector-burner, able to burn a mixture of NG with H_2 up to 100% with oxygen in order to preheat and cut the scrap, as well as to inject oxygen to decarburize the steel bath.

CFD simulations have been carried out to analyze in detail the combustion phenomena of NG and H_2 with the following method:

1) Reynolds Averaged Navier Stokes (RANS) approach to numerically solve turbulent flows. In RANS approach the Navier Stokes equations are reported in a time averaged form and solved.
2) Discrete Ordinates (DO) model to describe the radiative heat transfer.[5]
3) Eddy Dissipation Concept Model (EDC) to describe the evolution of the chemical species during the combustion. The chemical reactions are modeled using the GRI-Mech 3.0 reaction mechanism, which consists of 325 reactions that involve 53 species.[4]

The different characteristic parameters of the combustion of H_2 and NG with oxygen show some important difference (reported in Table 1[3]) that must be considered when designing a burner that must work with both.

Table 1: Comparison of the main parameters of NG and H_2

Parameter	Natural Gas	Hydrogen
Ignition temperature (°C)	556	560
Adiabatic Flame Temperature (°C)	2780	2806
Flammability limit (%)	From 5.4 to 59	From 4 to 94
Flame speed (cm/s)	30-40	200-300

Based on the data reported in Table 1 (wider H_2 flammability limits and higher flame speed), it can be noted that H_2 is much more reactive than NG and this impacts the design of the burner.

1.1 CFD H_2 injector-burner modeling results

CFD results have shown that the increase of the H_2/NG ratio increases the maximum flame temperature and moves the maximum temperature closer to the burner tip. Figure 1 shows the contours of the main thermo-fluid dynamic fields of the H_2 injector-burner operating at 3 MW with 100% H_2.

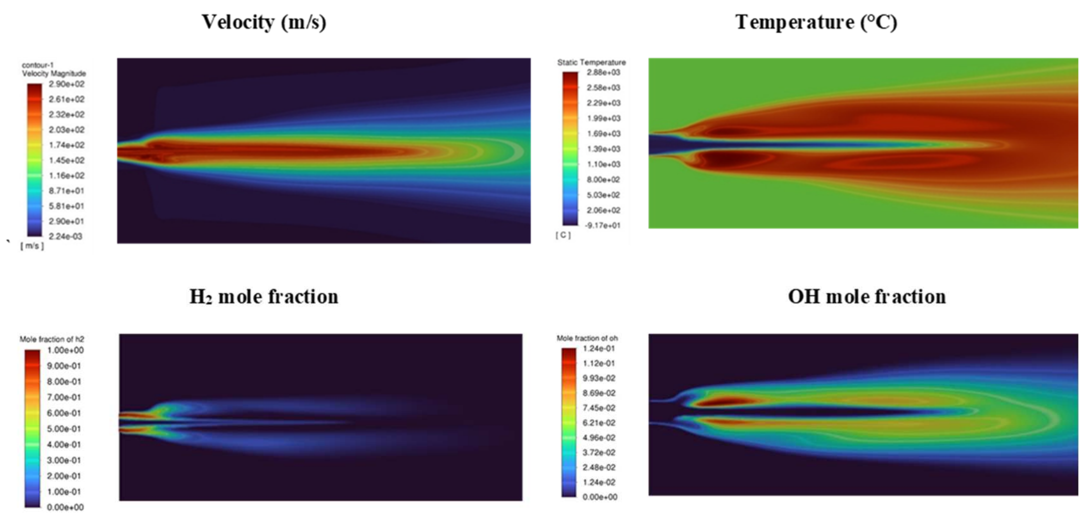

Figure 1. Characteristics of the 3 MW flame fed with 100% hydrogen

Thanks to the mixing of oxidant and oxidizer and the fast ignition, H_2 combustion is completed in a short distance, with the strong central oxygen jet that improves the flame stability. Moreover, central oxygen high stability allows to work with an elongated flame having a progressive combustion through the entire jet length.

1.2 H_2 injector-burner structure

Results of simulations of combustion and water cooling have been used to define the H_2 injector-burner design. It is a monolithic structure with openings in the front face for fuel and oxygen. Central oxygen is fed through a shaped convergent-divergent nozzle. The copper body is efficiently water cooled.

Openings for oxygen and fuel in the front copper head (including the oxygen nozzle) have been designed in order to protect the tip from clogging phenomena. H_2 injector-burner includes inlets for oxygen and fuel streams and inlet/outlet for cooling water.

Figure 2 shows the H_2 injector-burner, in a 3D model and after manufacturing, ready for installation in the steel plant.

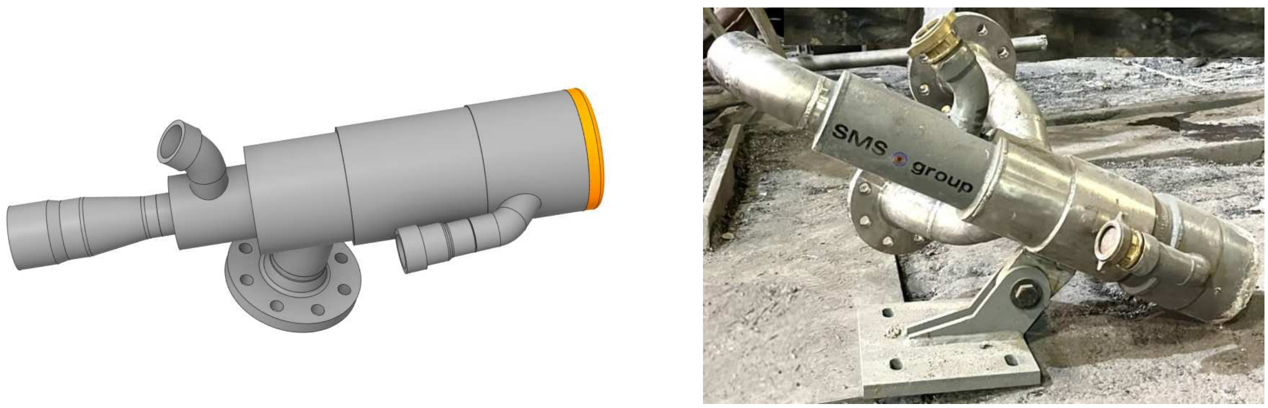

Figure 2. H_2 Injector-burner

2. Laboratory scale tests

Tests have been performed with laboratory scale H_2 injector-burner prototypes as a complementary task in parallel during CFD simulation of flame and cooling. Later, test has been performed in a pilot scale EAF in order to assess the absence of hydrogen pickup in the steel melt before performing the industrial scale tests. All laboratory scale H_2 injector-burners prototypes for tests have been manufactured by means of metal additive manufacturing.

Flame in open environment has been tested at RWTH-IoB in Aachen (as shown in Figure 3) using a 50 kW prototype.

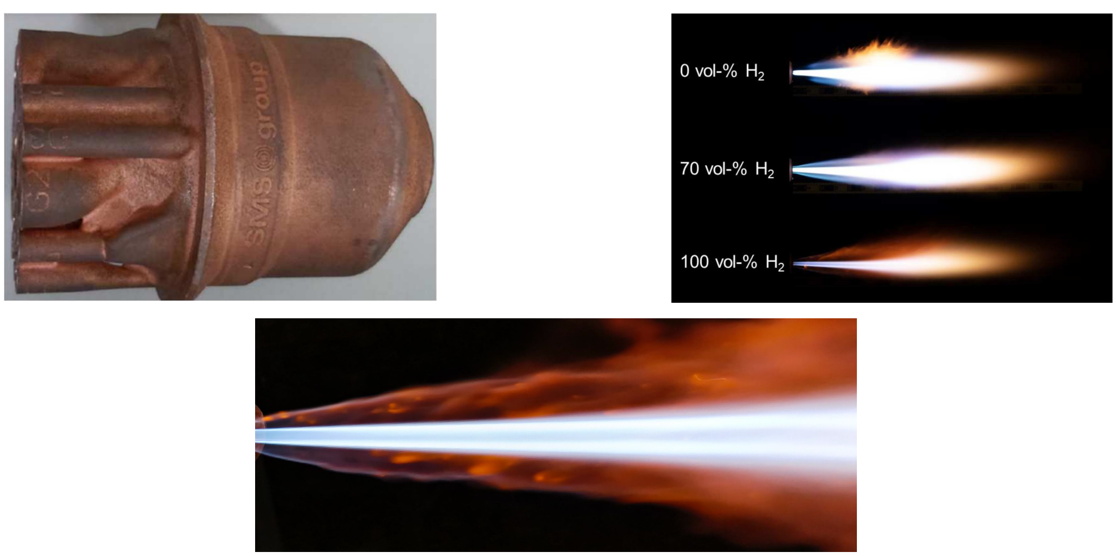

Figure 3. Free flame test

Apart from obtaining a long and stable flame in all conditions, it was observed that the ignition point got closer to the injector-burner tip. This result, together with the higher flame temperature obtained when burning hydrogen, has been used as input for the development of the injector-burner cooling.

After that, another lab scale H_2 injector-burner prototype (400 kW power) has been manufactured for testing the effectiveness of the cooling in a long run test (1600 °C for 20 hours) in a lab scale combustion chamber (at GWI - Gas und Warme Institute in Essen). The H_2 injector-burner proved the effectiveness of the cooling, since at the end of the test it appeared as after manufacturing (Figure 4).

Figure 4. Small scale prototype for long run test

After all these tests have been completed, a trial for assessing the eventual hydrogen pickup has been conducted in the lab scale EAF of RWTH-IoB in Aachen (200 kg capacity –Figure 5) with the additively manufactured laboratory scale 50 kW H_2 injector-burner prototype. Various tests have been performed, operating the H_2 injector-burner prototype either during boring phase or during flat bath phase to simulate both scenarios.

After tapping, steel has been subjected to chemical analysis and microscopic examination. This analysis showed that none of the samples had any pores that could have been caused by hydrogen pick-up. The low hydrogen levels detected in the samples as well as the microscopic analysis indicate that the use of a H_2 injector-burner does not affect the hydrogen pick-up of the steel.

Figure 5. Lab scale EAF at RWTH-IoB in Aachen

3. Combustion chamber full scale tests

In order to evaluate the H_2 injector-burner performance, an experimental campaign at RINA-CSM combustion chamber in Dalmine has been carried out. These experimental trials represented a propaedeutic step to verify the functionality of the H_2 injector-burner at its 4 MW full scale power and to identify optimal operative conditions to be adopted at industrial scale tests in Pittini Ferriere Nord and Celsa Barcelona.

The RINA-CSM combustion chamber (Figure 6) is a very well established and proven facility having the following characteristics:

- internal section: 2 x 2 m
- internal length: from 3 to 7.5 m (modular, for the tests the full length has been implemented)
- maximum allowable burner capacity: 3 MW
- maximum fuel flow rate: 300 Nm^3/h of NG, 2000 Nm^3/h for syngas compositions
- maximum comburent flow rate: 3500 Nm^3/h of AIR
- maximum working temperature: 1250°C

The combustion chamber has been equipped with thermocouples, flow rate and pressure measurements of the H_2, NG, O_2 inlet lines and off-gas analyzers to monitor the combustion process (O_2, CO, CO_2, and NOx). In the lower part of the combustion chamber a series of thermocouples have been inserted along longitudinal axis to evaluate the temperature distribution along the entire length of the combustion chamber. The combustion chamber has been also equipped with movable cooling lances (to balance the heat load generated by the flame) and with a fully automatic control system for the reliable and precise execution of the tests.

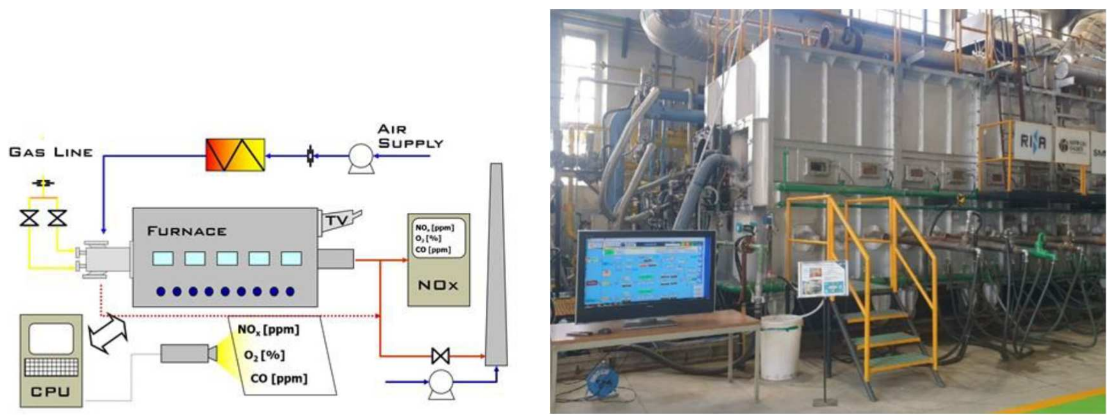

Figure 6. Combustion chamber at RINA-CSM in Dalmine

Experimental campaign at RINA-CSM combustion chamber has been performed from 100% NG to 100% hydrogen, including mixed configurations of H_2-NG, and feeding pure oxygen as comburent.

To feed and control the H_2-NG mixture to the burner, a dedicated mixing and regulating valve stand called FSRS (Fuel Supply and Regulation System) has been installed, receiving NG from the local existing supply and H_2 from a dedicated tube trailer (see Figure 7).

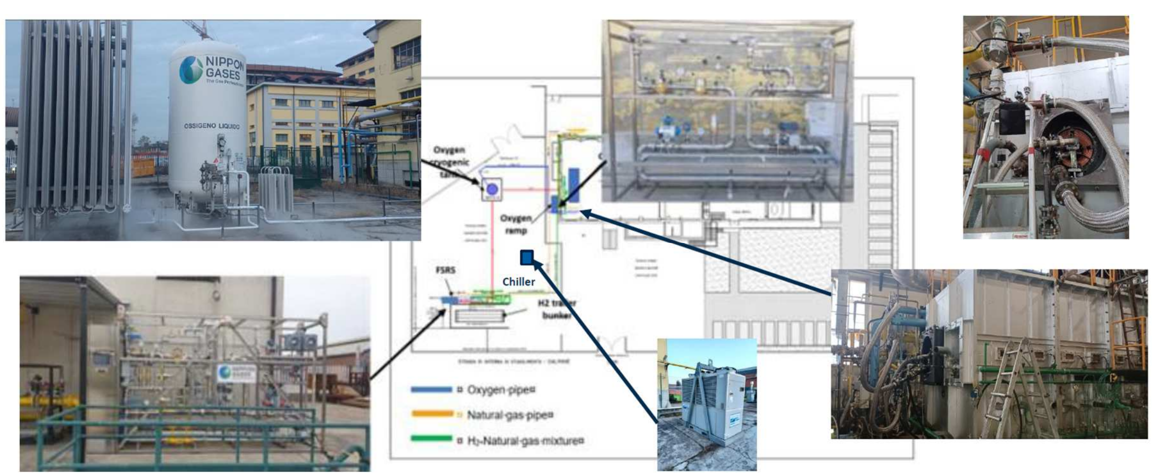

Figure 7. Overall scheme and picture of the RINA-CSM combustion chamber facility

For the feeding of oxygen, a cryogenic tank of 10.000 liters and a dedicated valve stand have been installed.

The burner cooling has been guaranteed by a dedicated chiller, with all the temperature and flow rate requirements exactly and continuously measured and regulated. The chiller has been used only for the specific test in RINA-CSM combustion chamber since, for the cooling of the burner in the EAF, the usual water-cooled box is used.

After the installation of all the equipment, a series of cold tests with nitrogen have been carried out in order to verify the proper functionality of each component and to achieve a fine tuning of the feeding system and the regulation parameters.

Once the entire system has been validated, all the hot pilot trials in RINA-CSM combustion chamber have been carried out with the target to verify the performance of the H_2 injector-burner in preparation for the industrial trials, especially regarding:

- the stability of the burner at high temperature with different power level and with different combustion ratio
- the thermal field and heat transfer in the furnace at different power output of the H_2 injector-burner
- the development of the flame, its appearance and ignition.

Moreover, the characteristics of the off gas in terms of composition and temperature have been measured.

The H_2 injector-burner has been tested at various power (from 1 to 3 MW), with various percentage of NG and H_2 (up to 100% of H_2) and with different combustion ratio (1.05 and 1.2), always at a chamber temperature of 1250 °C (see Table 2).

Table 2. Tests performed in the RINA-CSM combustion chamber

Power	**Combustion ratio**	**H2%**
1	1.05 and 1.2	0%- 20%- 40%-60%-80%-100%
1.5	1.05 and 1.2	0%- 20%- 40%- 60%-80%-100%
2	1.05 and 1.2	0%- 20%- 40%-60%-80%-100%
2.5	1.05 and 1.2	0%- 20%- 40%-60%-80%-100%
3	1.05 and 1.2	0%- 20%- 40%-60%-80%-100%

Before the execution of each test, the furnace has been preheated above the self-ignition temperature using two NG auxiliary side burners. During the test execution, the same auxiliary burners have been used to inject air into the combustion chamber to simulate the air inlet in the EAF, for example through the slagging door of the EAF.

Figure 8 shows a series of pictures taken from the bottom end of the combustion chamber, to have a front prospective view of the flame appearance changing with the increase of H_2 percentage and/or power. It can be seen how the flame tends to become less visible when H_2 content is increased.

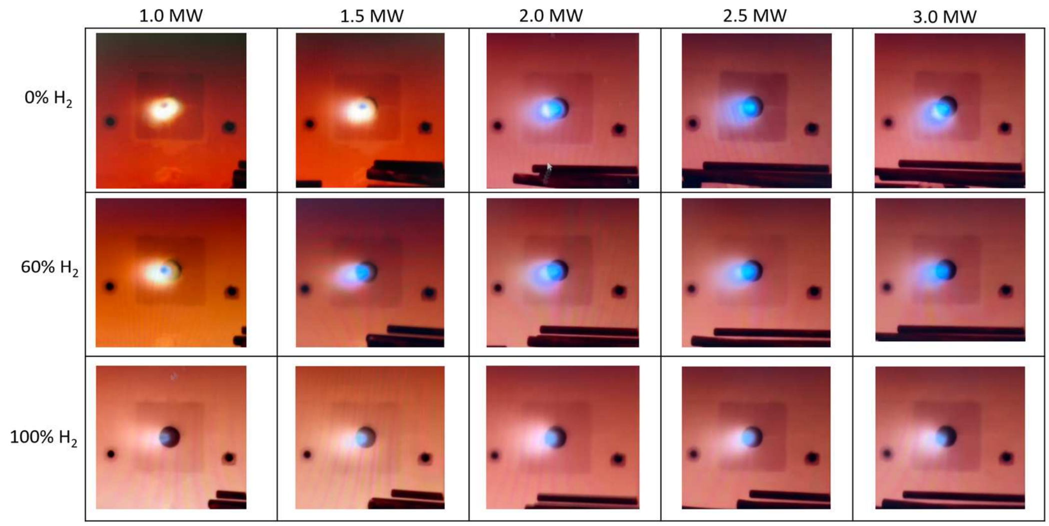

Figure 8. Flame appearance at various power and %H2 in front view

The flame becomes more elongated with the increase of power due to increase of the impulse (higher flow rate and high velocity), while the increasing of the hydrogen content decreases the brightness of the flame, which is almost disappearing when H_2 is above 60% (the color of the flame is covered by infrared emission of the wall).

Figure 9 shows the temperature distribution along longitudinal axis of the combustion chamber as function of power and fuel composition (to be noted that the temperature reduction inside the combustion chamber, for an increased injector-burner power, is caused by the increase of the heat extracted by cooling circuit of the furnace in the specific tests).

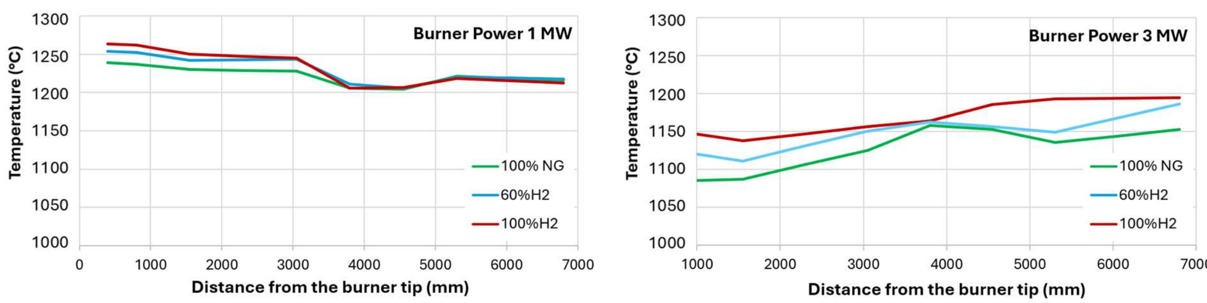

Figure 9. Temperature distribution along longitudinal axis of the combustion chamber - Effect of fuel composition

The increase of the percentage of H_2 in the fuel increases the temperature of the first thermocouple, which means that the H_2 is more reactive and start the ignition nearest to the burner tip.

At 1 MW there is a reduction of the temperature along the furnace while at 3 MW there is an increase of the temperature. This means that at 1 MW the combustion is completed in the first part of the combustion chamber, while at 3 MW the combustion seems to evolve for the whole combustion chamber length.

The trends reported in Figure 10 show the reduction of the percentage of CO_2 in the off-gas as function of the percentage of H_2 in the fuel. In order to reduce the percentage of CO_2 in the off-gas at 50% is necessary to use about 80% of H_2 in the fuel mixture.

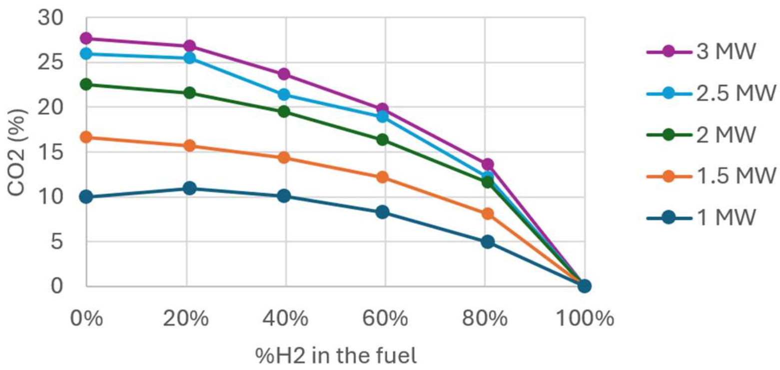

Figure 10. Trend of the CO2 percentage in the off-gas for various %H2 in in the inlet fuel

The experimental campaign was successfully carried out demonstrating that injector-burner is stable and works correctly up to 3 MW and with all the fuel compositions from 100% NG to 100% H_2 and for all the tested combustion ratios.

4. Industrial test of injector-burner in EAF

At the end, according to the project program, injector-burner has been installed in the EAF of Pittini Ferriere Nord in Osoppo (Italy) for testing in real production.

Ferriere Nord plant produces rebars and cold drawing steel via the EAF-LF-CCM route. With an EAF capacity of 155 ton tapped steel and a tap to tap time around 45’, the plant has a yearly production of 1.5 Mton steel.

The chemical package is composed by several auxiliaries. Focusing just on burners and oxygen injectors, the furnace is equipped with 8 oxygen-NG burners and 3 injector-burners (used as burners during the first phase of the heat and as oxygen injectors during the second phase). (Figure 11)

Figure 11. EAF of Pittini Ferriere Nord in Osoppo, Italy

The H_2 injector-burner has been installed replacing an existing burner, in the existing water-cooled box (to be noted that no modification to the water-cooled box nor to the sidewall panel were necessary). As shown in Figure 12, the H_2 injector-burner replaced the first burner on the left side of the slag door. In this way it has been possible to see the flame from the slag door, to make visual assessments and to make the installation easier since the feeding of the gases comes from the left side of the furnace.

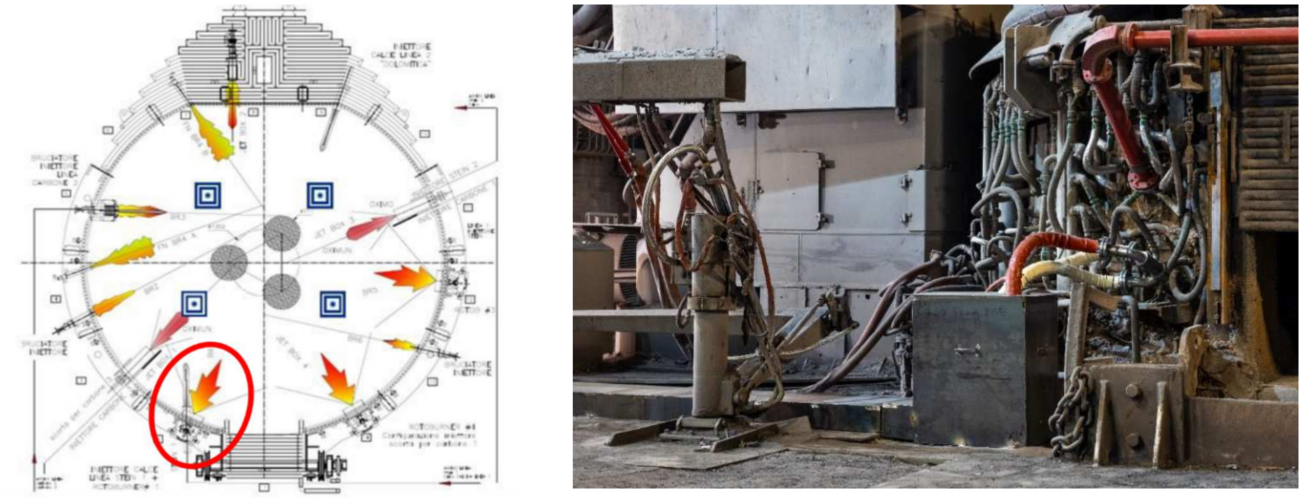

Figure 12. Pittini Ferriere Nord EAF chemical package layout and H2 injector-burner installation

The test was performed operating the H_2 injector-burner with the same flame profiles of the burner replaced. The profile had a first phase of flame to preheat the scrap with increasing power, followed by a phase of oxygen cutting. Then, during the decarburization phase, the burner was in standby with flushing, to prevent from being clogged by splashes of steel and slag.

Since the hydrogen was fed by means of a tube trailer, the duration of the campaign was defined by the total available volume of hydrogen. The industrial campaign had a duration of 4 days, during which the burner was operated with hydrogen only during the day shift. 20 heats (out of the 84 tapped in the 4 days of test) were performed feeding hydrogen with the H_2 injector-burner.

Since the effect of the replacement of only one burner would be diluted on the overall performance figures of the EAF, the hydrogen ramp up (50%, 75%) was very quick (two heats), performing 18 heats with 100% hydrogen. 13 heats (out of 20) were performed using the standard flame profile, while in 8 heats the thermal power delivered by the H_2 injector-burner was increased to 4 MW. In 4 of these heats, all other burners have been switched off, and the only operating one was the H_2 injector-burner. (Figure 13)

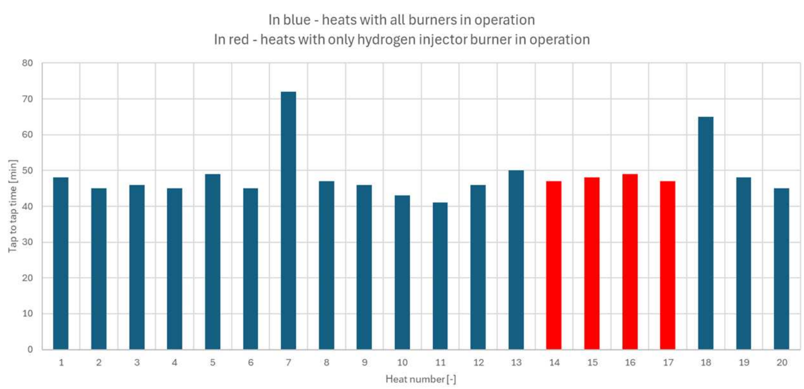

Figure 13. Tap to tap time in heats with all burners working and in heats with only the H_2 injector-burner in operation

As can be seen from Figure 13, in heat #7 a longer tap to tap time (70 min) was obtained because, before starting the heat, the flame generated by the H_2 injector-burner was observed from the slag door (Figure 14). In the other heats, the tap to tap time was in line with the burner fed with natural gas.

Figure 14. H_2 injector-burner flame observed from the slag door

Experimental trials using hydrogen demonstrated no relevant impacts on the EAF process. The replacement of only one of the eight NG burners with the new H_2 injector-burner demonstrated that the fundamental performance parameters as tap-to-tap time, steel temperature, specific electrical energy consumption and productivity have not undergone significant variations.

With reference to the burner replaced for the industrial test, compared to the standard practice used by Ferriere Nord, the reduction in CO_2 generation is shown in the following chart (Figure 15).

To be noted that the residual CO_2 production in most of the heats was due to the flushing flame (the low power flame which is maintained during the periods in which the burner is not required), which was fed with NG. In some of the heats this flushing flame was also fed with 100% H_2 and this cut to zero the CO_2 production, also validating the full operability of the H_2 injector-burner with pure hydrogen.

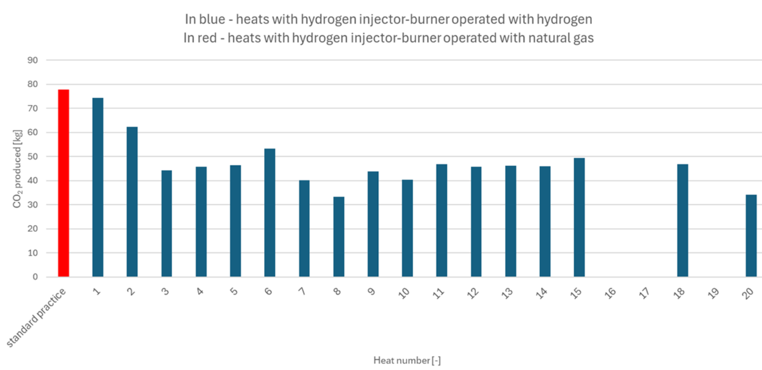

Figure 15. CO_2 production by the burner replaced for the industrial test

From the data analysis related to the residual and diffusible hydrogen content into liquid steel, no relevant influence of the H_2 utilization on the EAF process in terms of the final steel quality have been found. More in detail, even if there is a certain variability on the results, the hydrogen concentration both in the liquid steel and in the finished product is lower than 2.0 ppm H which is safe enough against metallurgical defects.

After the completion of the test with hydrogen, the injector-burner continued to work as per usual Pittini Ferriere Nord production for other 331 heats until the end of campaign (390 heats in total). The burner did not suffer any clogging and by also examining the front face of the burner, the outlet sections of oxygen and fuel were found to be totally clean. Figure 16 shows the flow rate used for anticlogging: it can be appreciated that it remained constant throughout the campaign. To be noted that, since the inlet pressure was fixed, the flow rate was used as a non-clogging indicator.

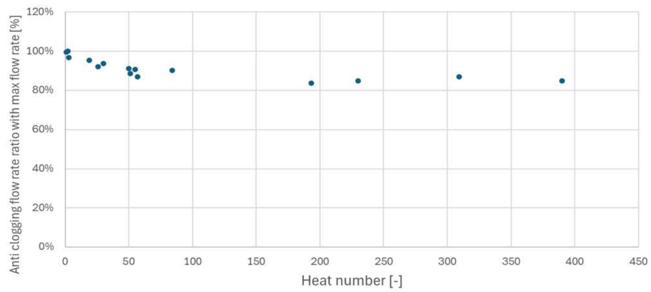

Figure 16. Anticlogging flow rate, with a fixed inlet pressure, during the campaign

In Figure 17 the burner is shown laterally, after the sand blasting cleaning. Focusing on the front face of the burner, it can be appreciated that the color of the copper remained the same as appeared immediately after burner construction. This means that the material did not undergo metallurgical modification thanks to the optimized design of the water cooling of the head and thanks also to the experience and the data obtained from the laboratory scale tests.

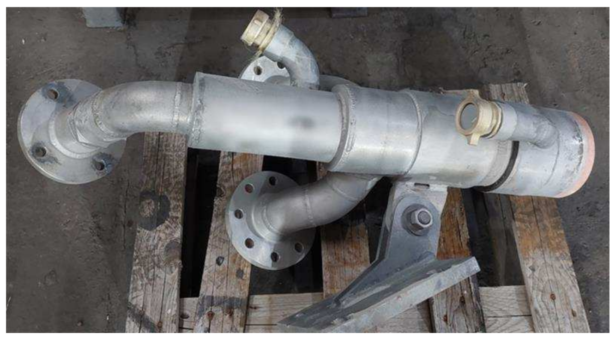

Figure 17. H_2 injector-burner after sand blasting at the end of the campaign

CONCLUSIONS

The development of an innovative H_2 injector-burner has successfully followed several steps, from early CFD simulations, through manufacturing of prototypes and their testing in dedicated laboratory facilities, until the realization of the full-scale units.

The H_2 injector-burner, designed for a maximum power of 4 MW, has been tested and completely characterized in full scale in a combustion chamber and then installed into a real EAF for testing during production.

The EAF tests have proven the reliability of the new H_2 injector burner and its application to the production without impacting the steel quality.

Further testing in a second EAF, replacing an injector-burner, are expected in the first half of 2025 for a further collection of data and information.

ACKNOWLEDGMENTS

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