Results from Experimental Campaign with the H2 Oxyfuel burner for Electric Arc Furnaces

E. L. Faraci[1*], I. Luzzo[2], L. Schulte[3], D. Gaspardo[4], J. Greguoldo[5], F. Vecchiet[5], G. Rinaldi[6], F. Ferrari[6], and F. Nastro[6]

[1]Rina Consulting – Centro Sviluppo Materiali, Via di Castel Romano 100, Rome (IT)
[2]Rina Consulting – Centro Sviluppo Materiali, Piazza Caduti 6 luglio 1944, Dalmine (IT)
[3]Rheinisch Westfaelische Technische Hochschule Aachen, Templergraben 55, Aachen (DE).
[4]Ferriere Nord s.p.a. Zona Industriale Fraz Rivoli, Osoppo UD (IT)
[5]SMS Group S.p.a., Via Udine 103, Tarcento (IT)
[6]Nippon Gases Italia S.r.l. Via Benigno Crespi 19 20159 – Milano (MI)

[*]E-mail: eros.faraci@rina.org

Abstract. This document presents experimental campaigns evaluating the use of hydrogen (H_2) burners in Electric Arc Furnaces (EAFs) for steel production. The pilot-scale EAF at RWTH-IOB was equipped with a 50 kW burner capable of operating with natural gas and hydrogen mixtures. The experiments aimed to analyze the impact of the H_2 burner on EAF operation and steel chemistry, with particular focus on hydrogen absorption. Results showed that hydrogen content in steel samples remained in the range of 2-5 ppm, indicating no negative impact on steel quality.

A preliminary experimental campaign with an Oxyfuel burner was conducted at the RINA-CSM combustion laboratory in Dalmine to evaluate the performance and feasibility of the burner with different fuel supplies, ranging from 100% natural gas to 100% hydrogen. The H_2 burners demonstrated good operational stability at high power levels (up to 3 MW) and with high hydrogen concentrations, achieving stable operating conditions quickly. The average heat transferred to the water of the cooling lances was 61% at 1 MW and 74% at 3 MW.

The industrial experimental campaign at FENO EAF (155 tons capacity) involved replacing one of the existing burners with a new H_2 burner unit. The trials aimed to assess the feasibility of using H_2 in EAF while maintaining steel quality and ensuring safety. The H_2 burner was tested under various operating modes across 20 heats. Steel samples showed some variability in hydrogen content but consistently remained below 2 ppm—within safe limits and free of defects. The global average CO_2 reduction achieved by replacing one existing burner with a new H_2 burner is about 6-8%.

The trials confirmed safe operation with strict monitoring and safety protocols, ensuring no adverse effects on furnace operation or steel quality. These results support the adoption of hydrogen burners in EAFs as a viable and effective solution for reducing greenhouse gas emissions and enhancing the sustainability of steel production—without compromising steel quality or operational safety.

1. Introduction

In the modern EAF, the contribution of 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. It means that the production of 100 tons of steel requires the combustion of 370-750 Nm^3 of NG with CO_2 emission of 0.75-1.5 tons. The substitution of NG with hydrogen in the EAF steel production will bring a remarkable reduction of CO_2 emission.

In this frame the RFCS project "*Developing and enabling H_2 burner utilization to produce liquid steel in EAF*" DevH2forEAF is in line with the European roadmap toward achieving zero greenhouse gas emissions. The project focuses on the design and realization of burners for EAF, able to work with NG/H_2 mixture, up to 100% hydrogen. The fuel mixing was performed by a dedicated mixing regulation system developed by Nippon Gases. These experimental trials represent a preliminary step to verify the functionality of the H_2 burner and to identify the optimal operating conditions for industrial-scale tests at Ferriere Nord.

2. Experimental trials in pilot scale EAF

2.1 Preliminary free-flame tests

A downscaled version of the burner, used in the industrial trials, was tested at the IOB. The burner has a power of 50 kW and is able to combust different fuel gases and their mixtures ranging from 100% natural gas (NG) to 100% hydrogen (H_2).

Before the installation of the burner in the pilot scale EAF, free-flame trials were carried out for a preliminary analysis of the flame. The burner was mounted on a stand in front of a black background including a measuring tape. In the free-flame trials 11 fuel gas compositions were investigated keeping the power of the burner constant at 50 kW. Figure 1 shows long exposure pictures of the free-flame trials for various percentages of H_2 of fuel gas composition.

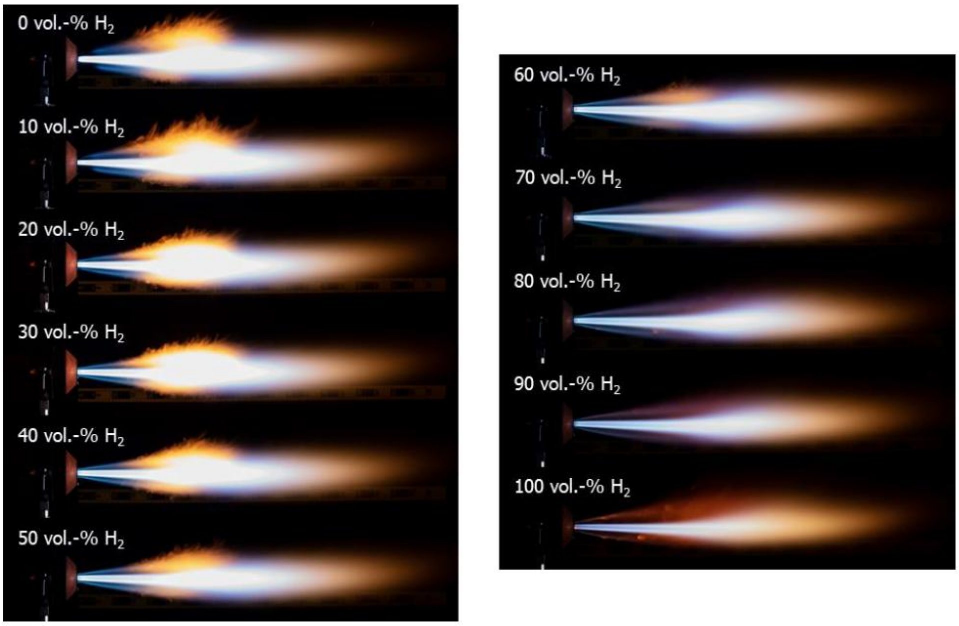

Figure 1. Free-flame trials of 50 kW burner for different fuel gas compositions

Figure 1 shows that the flame is visible for all fuel gas compositions and the addition of hydrogen to the fuel gas the flame increasingly stabilized itself. For all fuel gas compositions, the length of the visible flame is in the same range, and sufficient for the application in the pilot scale EAF. With the substitution of natural gas by hydrogen up to 60% an orange flame is visible. Even for the flame with 100% hydrogen in the fuel gas a flame is visible, due to particles present in the ambient atmosphere which accumulate in the long exposure picture.

2.2 Burner trials in EAF

The pilot scale EAF is gas-tight and water-cooled furnace with an active power of 600 kW and 2000 A of maximum arc current.

The experimental trials have been conducted charging 117 kg of iron scrap, Table 1 repots the type and quantity of materials charged in the EAF.

Table 1: Charged materials in EAF

Material	Weight (kg)
Iron flakes	50
Anthracite coal	1.3
Dololime	3
Screws from railroad sleepers	67

During the burner on phase electric arcs with a lower energy were still present to make up for the energy losses of the furnace and keep the steel molten.

However, when the electrical energy is switched on, the flame can no longer be identified through the window because of the bright light coming from the arcs and the smoke in the furnace atmosphere. The indicator for an existing flame is in this case the off-gas analysis with the hydrogen content of the off-gas. Table 2 reports an overview of all trial conditions three experimental trials.

Table 2: Composition of the material input

	Trial 1	Trial 2	Trial 3
Fuel gas	100%H_2	100% H_2	100% H_2
Operation mode	Flat bath, then burner	Burner during the melt down	Burner during the melt down
Problems	Start of the burner while the electric arcs are present	Burner ignition without ignition electrode	Water leakage at the electrodes in the last minutes

In the first trial, the burner was ignited after the complete meltdown of the scrap, requiring the furnace to be turned off and opened. However, ignition failed due to low arc parameters and off-gas signals. In a second attempt, the electric arcs were turned off, allowing successful burner ignition. Once the arcs were reactivated, stable operation was achieved.

In the second trial, the burner operated from the start for about 80 minutes. Although the scrap was well-heated, it did not reach melting temperature, and the process was completed using electric arcs at 120–140 kW.

The third trial repeated the first setup to verify results, as it was expected to yield the highest hydrogen pick-up. However, after 25 minutes of burner operation, a water leak in the electrode cooling system forced an early shutdown.

Figure 2 shows the power distribution between the electric arcs and the burner for trial 3.

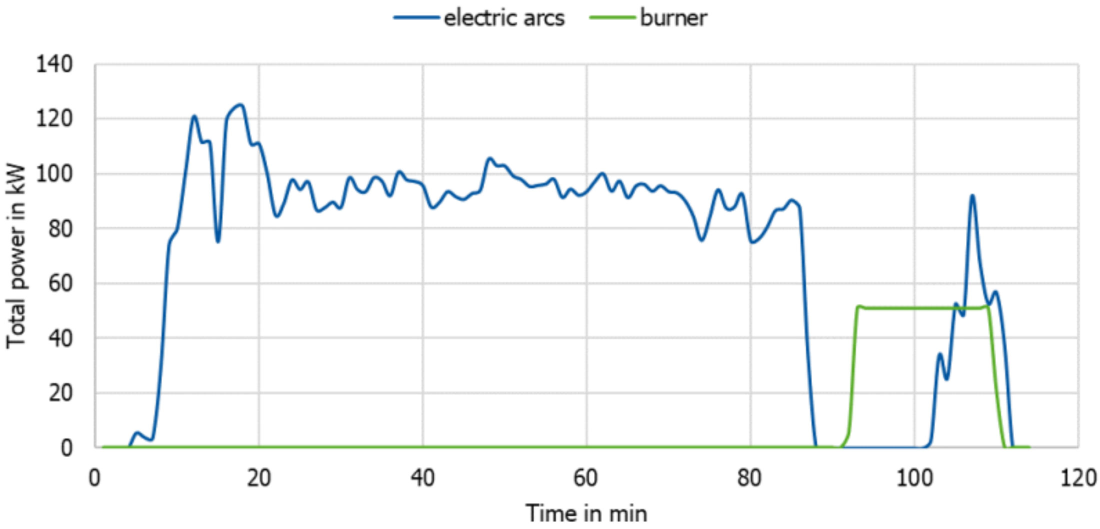

Figure 2: Operation diagram for the power input via the arcs and the burner for trial 3

2.3 Steel and slag analysis

Hydrogen solubility in molten steel depends on factors such as hydrogen partial pressure, temperature, melt composition, and the free surface area exposed to gas. Literature reports values between 21.8 and 27.9 ppm for pure iron at 1600 °C and 1 atm H_2. According to Sieverts' law, solubility is proportional to the square root of hydrogen partial pressure and increases with temperature. Elements like Al, C, O, P, S, Si, and Sn increase hydrogen solubility, while Cr, Cu, Mn, Ni, Ti, and V decrease it. [1,2,3,4]

To assess the impact of the H_2 burner, steel samples were analyzed during EAF trials. All samples showed very low hydrogen content. In the first and second trials, hydrogen levels remained low or even decreased after burner use. Only in the third trial was a slight increase observed, likely due to a water leak in the electrode cooling system.

Figure 3 shows the concentration of the hydrogen in the steel picked up in various phases of trials.

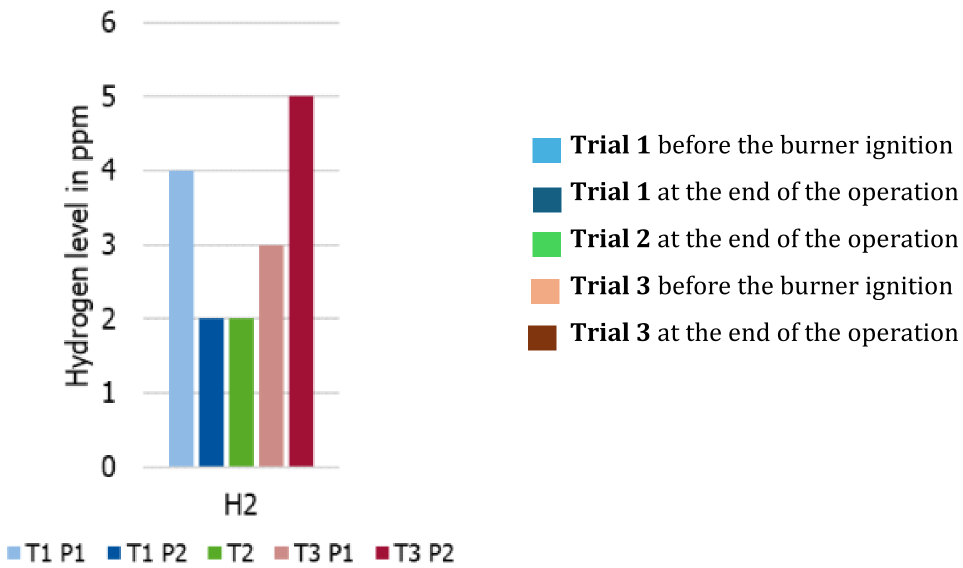

Figure 3: Hydrogen content in the steel

The results of the analysis in Figure 3 show that the H_2 content in the steel remined in the range of 2-5 ppm. However, the third test exhibited an increase in hydrogen content after using the H_2-burner. It is worth noting that water cooling leakage may have contributed to this phenomenon, leading to the observed rise in hydrogen content.

In addition to the chemical analysis, the microstructure of the steel samples was examined microscopically. This analysis showed that none of the samples had any pores that could have been caused by hydrogen pick-up.

3. Preliminary experimental campaign with Oxyfuel burner

The experimental campaign with an Oxyfuel burner was conducted, at the RINA-CSM combustion laboratory in Dalmine, to evaluate performance and feasibility of the burner with different fuels supplies: from 100% NG to 100% Hydrogen, including mixed configuration of NG-H_2. The fuel mixing was performed by a dedicated mixing regulation system developed by Nippon Gases.

3.1 Site preparation for the experimental trials

For the experimental tests on the H_2 burner with a thermal capacity up to 3 MW in RINA - CSM at Dalmine site has been installed and set up various equipment to provide, at safety conditions: oxygen, H_2, natural gas and water at flowrate and pressure requested.

These experimental trials represent a preliminary step to verify the functionality of the H_2 burner and to identify the optimal operating conditions for future industrial-scale tests at Ferriere Nord and Celsa production plants.

The H_2 Oxyfuel Burner was designed and built by SMS. The burner was tested in the modular furnace pilot plant at RINA-CSM with a maximum thermal load capacity of 3 MW. The burner has been installed in the modular furnace and connected to the hydrogen line. For the experimental tests the following equipment have been installed and set up:

1) Cryogenic oxygen tank with the capacity of 10.000 Liters.
2) FSRS (Fuel Supply and Regulation System) to provide NG and H_2 mixture at proper flow rate composition, and pressure.

3) Oxygen ramp to provide Oxygen at the target flow rate and pressure.
4) Dedicated water-cooling circuit (comprising chiller) to cool the burner (of the same type to water cooling circuits installed in EAFs).
5) The modular furnace equipped with the H_2-burner

Figure 4 shows the location of the main equipment installed in RINA-CSM Daline in order to perform the experimental tests with the H_2 burner

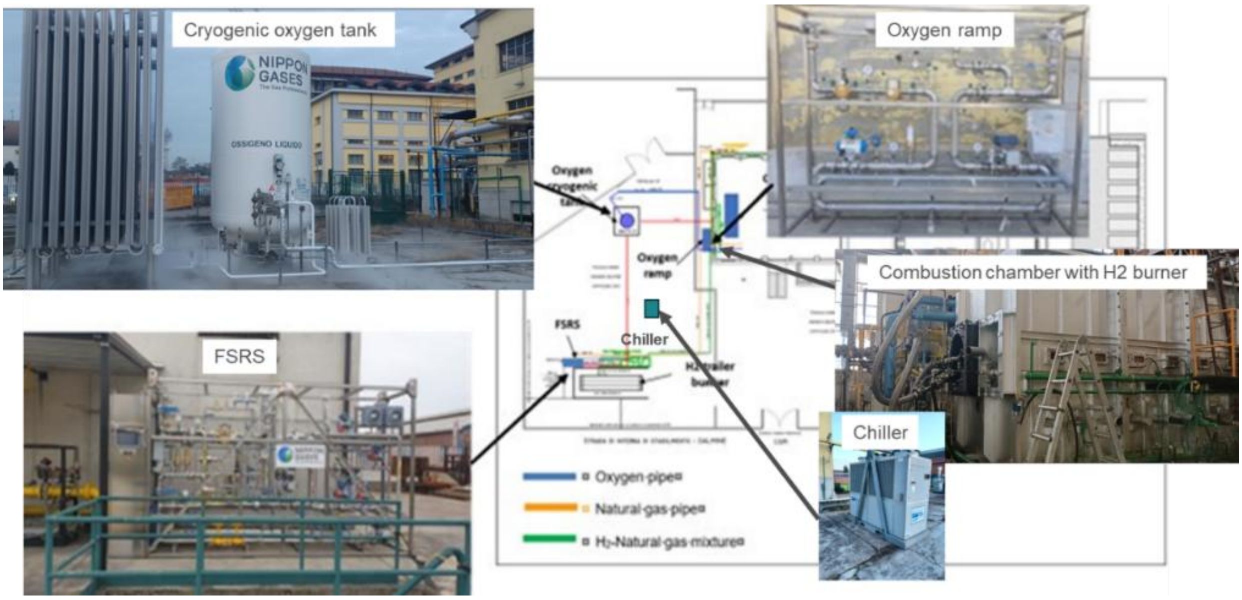

Figure 4: Location of the main equipment for the H_2-burner experimental trials at RINA-CSM Dalmine

The cryogenic oxygen tank, the FSRS and the Oxygen ramp was provided by Nippon Gases with a tailor-made solution for RINA-CSM combustion station.

The modular furnace has been equipped with thermocouples, flow rate, and pressure sensors for the H_2, NG, and O_2 inlet lines, along with off-gas analysers. Flue gas analysis has been conducted intermittently for O_2, CO, NOx, and CO_2 to ensure accurate monitoring of the combustion process.

3.2 Experimental trials

The experimental campaign has been carried out, with the objective to verify performance of the H_2 - burner in preparation for the industrial trials. These tests have permitted to evaluate:

1) The stability of the burner at high temperature with different level of the power and with different combustion ratio
2) The thermal field and heat transfer in the furnace at different power input
3) Oxygen amount in flue gas

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

The H_2 burner has been tested at various power (from 1 to 3 MW) and various percentage of NG and H_2 (up to 100% of H_2) and with different combustion ratio (1.05 and 1.2) at 1250 °C.

Table 3 synthetizes the tests experimental trial program.

Table 3: Experimental trial program

Power	Combustion ratio	%H_2
1	1.05 and 1.2	0%- 20%- 40%-60%-80%-100%
2	1.05 and 1.2	0%- 20%- 40%-60%-80%-100%
3	1.05 and 1.2	0%- 20%- 40%-60%-80%-100%
4	1.05 and 1.2	0%- 20%- 40%-60%-80%-100%
5	1.05 and 1.2	0%- 20%- 40%-60%-80%-100%

Based on the results of the experimental campaign, several key conclusions can be drawn:

1) The H_2/NG flow rate remained stable, even at 3 MW and high hydrogen concentrations. Stable operating conditions were achieved within minutes for each tested point. The flame straightened as power increased, a result of the higher impulse due to greater flow rate and velocity. With higher hydrogen content, the flame's luminosity decreased, disappearing entirely when the hydrogen concentration exceeded 60% (Figure 5).

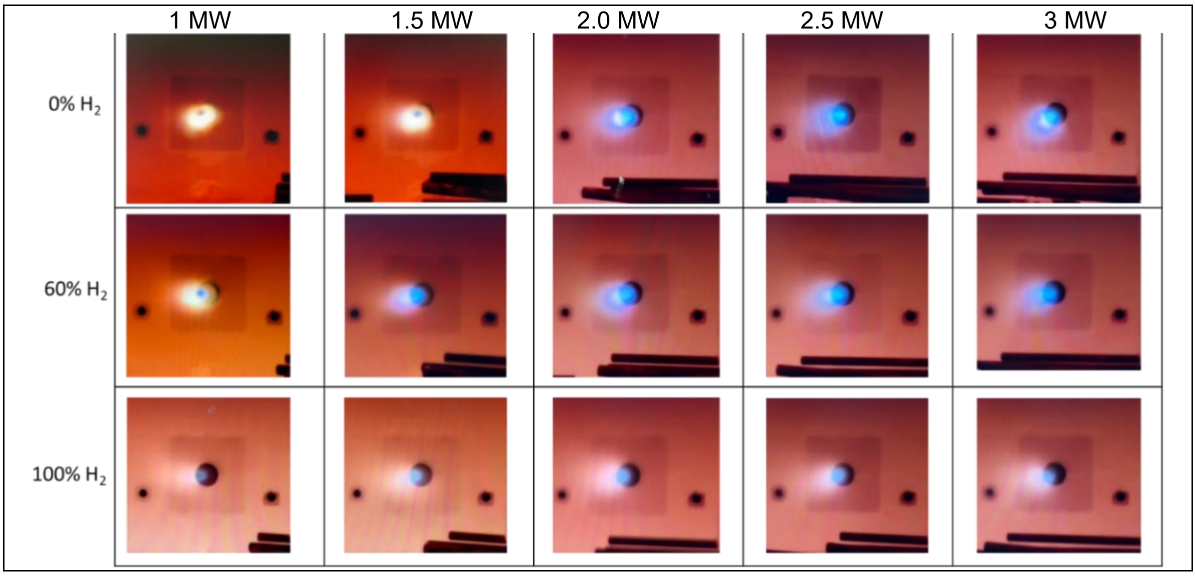

Figure 5: Flame colour at various power and %H_2-front view

2) An increase in hydrogen content led to a rise in temperature at the first thermocouple, indicating that hydrogen is more reactive and initiates ignition closer to the burner tip. At 1 MW, temperatures decreased along the furnace, while at 3 MW, they increased, suggesting complete combustion in the first part of the chamber at 1 MW, whereas at 3 MW, combustion continued throughout the entire chamber.

3) The average heat transferred to the water of the cooling lances (which can be considered as scrap in the EAF) was 61% at 1 MW and 74% at 3 MW, attributed to the longer cooling lances necessary to maintain furnace temperatures below 1250°C.

4) NOx measurements for all operating points exceeded the instrument's full-scale range (2000 ppm), with no soot or CO production observed. The high NOx emissions are likely due to air inside the furnace, simulating the slagging door opening. Working with no air inside the furnace (i.e. simulating closed slag door) the NOx emission would be greatly reduced. To reduce the CO_2 percentage in the off gas to 50%, approximately 80% hydrogen is needed in the fuel mixture.

4. Industrial experimental trials with Oxyfuel burner

4.1 Introduction

The experimental campaign at the FENO Electric Arc Furnace (EAF) aimed to evaluate the feasibility of using a hydrogen (H_2) burner to replace one of the existing natural gas (NG) burners. The primary goals were to assess the impact on steel quality and ensure safety. The trials were conducted in accordance with the results of pilot laboratory tests and preoperational tests at FENO EAF.

The FENO EAF has a diameter of 7.10 meters and a capacity of 155 tons. It is equipped with 8 natural gas burners with a maximum power of 4 MW, 4 jet burners with a maximum power of 3 MW, and 3 bottom tuyeres fed with oxygen. Additionally, the furnace is equipped with injectors for slag reducing agents and slag conditioners.

Figure 6 shows the FENO EAF layout with the H_2-burner clearly indicated by a red circle.

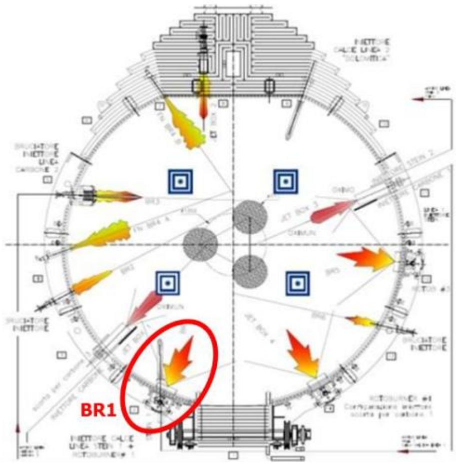

Figure 6: Layout of FENO burner location in the EAF

4.2 Experimental trials preparation

The experimental trials were planned for three consecutive days. The first day was dedicated to setup operations, while hydrogen tests were conducted on the following two days. The trials aimed to identify the best conditions to maximize the use of hydrogen without impairing steel quality and ensuring safety.

The trials were planned for two consecutive days, starting on October 28, 2024. The activities included:

- Day 1: Plant downtime for maintenance, installation of the H_2 burner, and initial heats with 100% NG.
- Day 2: Tests with varying H_2 flow rates (25%, 50%, 75%, 100%).

The operating mode are reported below

- **Active Burner Mode**: Power set point received remotely, leakage check, calculation of required oxygen flow rate, and stoichiometric ratio monitoring.
- **Anti-Splash Mode**: Set points for oxygen and methane, stoichiometric ratio monitoring.
- **Purging Mode**: Nitrogen used to flush out residual gases.
- **Anti-Clogging Mode**: Nitrogen used to prevent blockage of burner channels.

4.3 Experimental trials in FENO EAF

The trials lasted three days, with approximately 3,800 Nm^3 of hydrogen used. The H_2 burner was tested at its maximum power (4 MW) and with a 100% H_2 flow rate. Twenty experimental trials were conducted, with the H_2 burner. The trials included tests with the hydrogen burner on and all others turned off, and tests with anti-splash mode using hydrogen/oxygen instead of NG/oxygen.

A detailed summary of the tests performed at FENO EAF, containing all the critical issues found in each heat, is shown in Table 4.

Table 4: Experimental data

DevH2forEAF - Test H2 burner in FENO EAF (Day 1)

Number of H2 Test	N° Heat	Steel Grade	N° Basket	% H2	Max Deliv. Power
1	7786	FE34+B	1	50	3.0 MW
			2	50	
2	7787	FE34+B	1	75	3.0 MW
			2	75	
3	7788	FE34+B	1	100	3.0 MW
			2	100	
-	7789	FE34+B	1	0	3.0 MW
			2	0	
4	7790	FE34+B	1	100	3.0 MW
			2	100	
5	7791	FE37+B	1	100	3.8 MW
			2	100	
6	7792	FE37+B	1	100	4.0 MW
			2	100	
7	7793	FE37+B	1	100	4.0 MW
			2	100	
8	7794	FE37+B	1	100	3.8 MW
			2	0	
9	7795	FE37+B	1	100	3.1 MW
			2	100	
10	7796	FE37+B	1	100	3.0 MW
			2	100	

DevH2forEAF - Test H2 burner in FENO EAF (Day 2)

Number of H2 Test	N° Heat	Steel Grade	N° Basket	% H2	Max Deliv. Power
11	7815	FE50	1	100	2.9 MW
			2	100	
12	7816	FE50	1	100	3.0 MW
			2	100	
13	7817	FE50	1	100	3.0 MW
			2	100	
14	7818	FE50	1	100	3.1 MW
			2	100	
15	7819	FE50	1	100	3.5 MW
			2	100	
16	7820	FE50	1	100	3.7 MW
			2	100	
17	7821	FE50	1	100	3.6 MW
			2	100	
18	7822	FE50	1	100	3.1 MW
			2	100	
19	7823	FE50	1	100	2.9 MW
			2	100	
20	7824	FE50	1	100	3.1 MW
			2	100	

On the basis of the data reported in the Table 4, the following consideration can be done:

1) The maximum delivered power was in the range of 3–4 MW.

2) For 16 heats, the H_2 burner was operated with 100% hydrogen, while the other burners were supplied with natural gas.

In order to evaluate the impact of the use of the hydrogen burner in the EAF furnace on the quality and chemical composition of the steel the sampling camping during the hydrogen experimental trials at FENO EAF was carried out. The samples have been collected in the LF inlet and then analyzed in the FENO Chemical/Quality Laboratory with the analytical instrument "LECO DH 603", allowing the determination of the hydrogen present in the steel of 12 different heats realized during the hydrogen experimental trials.

Figure 7 shows the results of the sampling campaign for the determination hydrogen content into the steel.

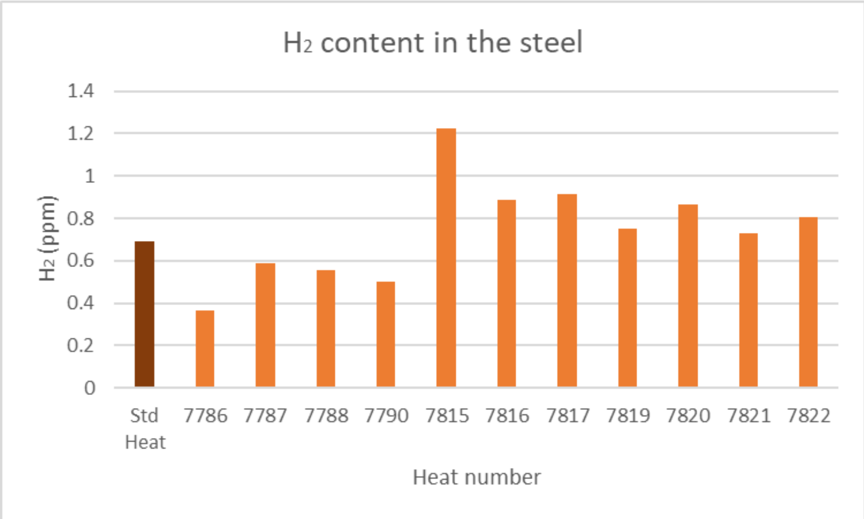

Figure 7: H_2 content in the steel

Figure 7 shows that:

1) In the standard heat (with NG burner utilization) the average content of H_2 in the steel is below 1 ppm
2) In the heats with H_2 burner there is a certain variability on the results, but the hydrogen concentration is always lower than 2 ppm which is safe enough against any type of defects.

The evaluation of the volumes of technical gases consumed during experimental trials has been carried out, in particular the amount of natural gas was used, and the relative avoided CO_2 emissions compared to those emitted in FENO standard operating practices, i.e. using only NG.

Figure 8 shows the NG consumption (Nm^3) and CO_2 reduction (expressed in percentage) with respect to a FENO standard heat using only Natural Gas. Those data refer only to the BR1 burner, i.e. the replaced burner with the new H2 burner manufactured by SMS.

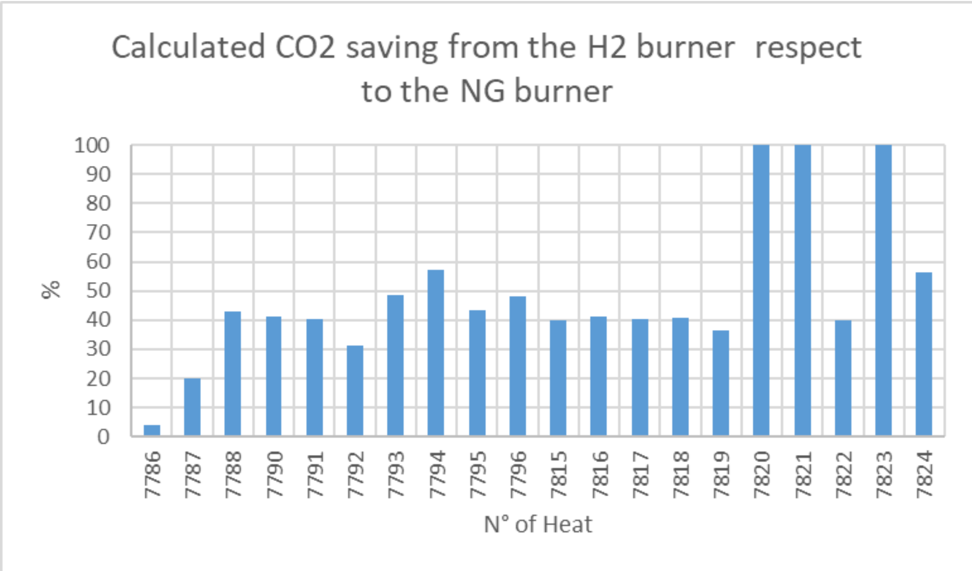

Figure 8: CO_2 saving from H2-burner respects natural gas burner

Figure 8 shows that the average CO_2 reduction achieved by the H_2 burner is approximately 48%, even when operating with 100% hydrogen, due to the continued use of natural gas during the anti-splash phase. For three heats, however, a 100% CO_2 reduction was achieved, as the other burners were turned off and hydrogen was also used during the anti-splash phase.

A calculation of the total CO_2 production related to the chemical energy supplied by natural gas burners and replacing one existing burner with a new H_2 burner showed a 6-8% decrese in CO_2

5. Conclusions

The experimental campaigns demonstrated the feasibility of using hydrogen (H_2) burners in Electric Arc Furnaces (EAF) without impairing steel quality and ensuring the highest level of safety. Here are the detailed conclusions:

1) <u>EAF Pilot scale trials:</u>

- H_2 content in the steel after using the H_2-burner is only a few ppm for all samples, moreover the microscopic examination of the steel samples showed no pores caused by hydrogen pick-up. This confirms that hydrogen burners do not compromise the structural integrity of the steel.

2) <u>Preliminary experimental campaign with oxyfuel burner:</u>

- The hydrogen burners demonstrated good operational stability even at high power levels (up to 3 MW) and with high hydrogen concentrations. Stable operating conditions were achieved quickly for each tested point.
- The average heat transferred to the water of the cooling lances (which can be considered as scrap in the EAF) was 61% at 1 MW and 74% at 3 MW, attributed to the longer cooling lances necessary to maintain furnace temperatures below 1250°C.

3) <u>Industrial experimental trial:</u>

- Experimental trials with the hydrogen (H_2) burner steel samples in LF were collected to assess the impact on hydrogen absorption and overall steel quality. The analysis revealed some variability in the results, but the hydrogen concentration consistently remained below 2.0 ppm, which is considered safe and does not lead to any defects.
- The H_2 burner achieved an average CO_2 reduction of 48% due to NG use during the anti-splash phase, while 100% reduction was reached in three heats where only hydrogen was used throughout.
- The global average CO_2 reduction achieved by replacing one existing burner with a new H_2 burner is about 6-8%.
- The substitution of NG with hydrogen in EAF steel production aligns with the European roadmap towards achieving zero greenhouse gas emissions, contributing to a more sustainable steel production process.

The various experimental trials confirmed that hydrogen burners can be used safely, with careful monitoring of operating conditions and emissions. The handling and utilization of hydrogen in the burners were conducted under strict safety protocols, ensuring no adverse effects on the furnace operation or steel quality.

These results support the adoption of hydrogen burners in EAFs as an effective solution to reduce greenhouse gas emissions and improve the sustainability of steel production. The successful implementation of hydrogen burners can lead to substantial environmental benefits while maintaining high standards of steel quality and operational safety. At the present, the transition from natural gas to hydrogen in electric arc furnaces (EAFs) is currently hindered by the lack of adequate infrastructure for hydrogen transportation and the high production cost of green hydrogen, which ranges between €90 and €210 per MWh, substantially higher than the approximate €40/MWh cost of natural gas. However, considering that green hydrogen production costs will decreases by around 50% by 2030 due to falling renewable energy prices and that the price of CO_2 will increase due to stricter EU climate targets, the use of H_2 in EAF could become economically viable very quickly.

Acknowledgments

This work was carried out with support from the European Union's Research Fund for Coal and Steel (RFCS) research program under the ongoing project: Development and enabling of the use of the H_2 burner to produce liquid steel in EAF – DevH2forEAF- GA number: 101034081.

References

[1] R. G. Blossey, R. D. Pehlke (1971). Solubility of hydrogen in liquid Fe− Co− Ni alloys. Metallurgical and Materials Transactions B 2, 3157-3161

[2] A. Sieverts, W. Krumbhaar, E. Jurisch (1911). The solubility of hydrogen in copper, iron and nickel. Z. Phys. Chem., 77, 591-591

[3] F. Gehrmann; Einfluss der Nitride von V, Nb und Ti auf die Diffusion und Löslichkeit von Wasserstoff in Eisen. VDI-Verlag. 1994

[4] T. Miki (2014). Dilute solutions. Treatise on Process Metallurgy. Elsevier. 557-585