DEVELOPING AND ENABLING H_2 BURNER UTILIZATION TO PRODUCE LIQUID STEEL IN EAF

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SUMMARY

In the Electric Arc Furnace (EAF) process the Natural Gas (NG) combustion provides 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 Nm3 of NG with an emission of 0.75-1.5 tons of CO2. In this frame EC funded RFCS project (Development and enabling of the use of the H2 burner to produce liquid steel in EAF – DevH2forEAF- GA number: 101034081) which has as its main objective the reduction of carbon footprint of EAF steel production. In order to achieve this objective a burner fed with hydrogen in place of the NG has been designed and realized. The project activities provides also a comprehensive analysis of H_2 hydrogen burners in EAF tackling both the technical and safety issues linked with utilization of H_2 into steelshop. Various experimental trials both on pilot scale and industrial ones will be carried out on 2024.

A burner able to work with a mixture of NG/H_2, ranging from 100% NG to 100% H2 has been designed, based on the results of the carried CFD simulation.

The complete H_2 pipeline to feed the burner has been designed, it is composed by: hydrogen tube trailer with decompression systems, fuel Supply Regulation System (FSRS) to mix various percentage of H_2 and NG. and flash-back arrestors system to protect the equipment from damage or explosion.

Main recommendations respect the safety conditions to minimize the H_2 leakage have been provided, moreover safety logics required in the hydrogen pipeline to guarantee the intrinsic safety of the equipment have been also indicated.

Key Words: Electric Arc Furnace (EAF), Hydrogen, Carbon Footprint Reduction, H2 burner, CFD burner simulation

1. INTRODUCTION

The reduction of carbon footprint represents the central goal of the European climate policy. The agreements of Paris (2015) establish the commitment of all the worldwide countries to keep the climate warming below 2°C until 2100, with the goal to limit the increase at 1,5°C. The reduction of carbon footprint, through the development and commercialization of new low-CO_2 technologies within the next 5-10 years, represents the central goal of the European climate policy. The efforts of European Commission are addressed to the identification, realization, and implementation of suitable solutions with a minimum impact on the environment. On steel sector, that is responsible for around 5% of CO2 emissions in the EU, RFCS funded research is promoting emerging and innovative technologies that impact at different levels on the transition of steel industries towards a zero-emission industry.

The steel production trough EAF has an increasingly important role in modern steelworks concepts. Today the EAF steel of the overall steel production in the EU-28 is 41.5 % (69 Mtons/year) but in in Italy (81%) and in Spain (61%), 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. In EAF process the 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 Nm3 of NG with an emission of 0.75-1.5 tons of CO2.

This article summarizes the activities carried out within the ongoing RFCS project (Development and enabling of the use of the H_2 burner to produce liquid steel in EAF – DevH2forEAF- GA number: 101034081) which has as its main objective the design and the realization of a H_2/NG EAF burner able to work up to 100% of H_2.

The H_2/NG burner has been designed and manufactured to work in severe environment, thus ensuring mechanical and thermal resistance in respect of EAF operative conditions

Chemical features of H_2 as combustible have been analyzed , in comparison to NG, resulting that the calorific value per Nm^3 of H_2 is lower than NG and flammability range is very broad (4-74% for combustion in air and 4-94% for combustion in oxygen).

In order to design the burner, CFD analysis has been carried out and the results in a burner with 100% of H_2 showed that:

a. The combustion of H_2 is complete in a few meters.

b. The central oxygen jet remains stable, improving the stability of the flame.

c. The fast ignition favors the mixing of oxidant and oxidizer.

d. The high speed of the central oxygen permits to produce an elongated flame with a progressively combustion through the entire length of the jet.

In accordance with the results of CFD simulation the burner has been designed and realized with fuel and oxygen inlets that permit to work up to 4 MW 100% H_2.

The main prescriptions to respect safety conditions for the H_2 pipeline in the steel shop have been defined:

1) For the H_2 pipeline realization stainless steel AISI-316 is preferable to AISI-304 due to mechanical properties, welding features and corrosion resistance. Stainless-Steel grades (AISI-316L, -316N, -316H, -316Ti) are recommended for critical process conditions but in each case also AISI-304 can be accepted for no-critical process conditions.

2) Welded joints are recommended wherever possible but where breakable joints (threaded, flanged etc.) are considered necessary, these should be kept to a minimum since they are a potential source of H_2 leakage. When flanged joints are used, ring joint flanges or weld-neck flanges are recommended (Ref. EN 1092-1). Compression fittings are not recommended on process lines because of the potential for hydrogen leakage.

3) Welding shall not be performed when the temperature of the metal surface within 305 mm (12 in.) of the point of welding in all directions is lower than 16°C. The work area and surfaces to be welded must be protected from wind and moisture conditions caused by ice, rain, snow, and running or standing water. Moreover peening is prohibited for all weldments, including weld metal buildup and repairs.

2. DESIGN AND REALIZATION OF EAF BURNERS, ABLE TO WORK WITH NG/H_2 MIXTURE, UP TO 100% HYDROGEN

1.1.1 CFD burner model set up

SMS designed the multi-fuel burner, according to EAF characteristics, that will be able to burn a mixture of NG with H_2 up to 100%.

CFD (Computational Fluid Dynamics) simulations have been carried out in order to analyze the combustion phenomena of NG and H_2. Fluid flow phenomena can be described by the Navier-Stokes equations for conservation of mass, momentum and energy whilst for the solving of species transport and turbulence, additional equations are necessary.

The numerical model for the simulation of the NG H_2 combustion consists of the burner geometry plus a large external volume in front of it, which represents a free gas volume within an EAF.

The mesh is produced within the SnappyHexMesh framework and consists of 16 milion mostly hexahedral volume elements (Figure 1). The finest mesh resolution is in front of the burner where most of the reaction takes place; in the zones far from the burner, the mesh is progressively coarser since less gradients are expected.

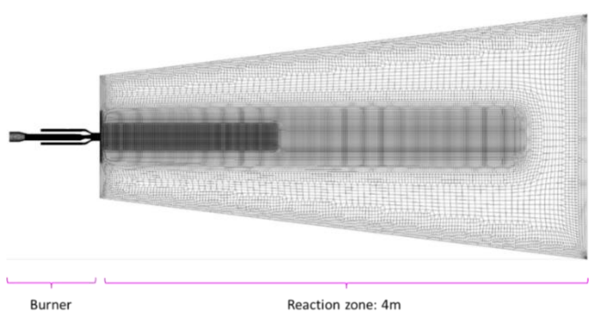

Figure 1 – *Computational mesh for the CFD simulation of the burner*

The chemical reactions are modeled using the methane-air reaction mechanism GRI-Mech 3.0 . The mechanism consists of 325 reactions that involve 53 species including nitric species for NOx predictions.

In order to obtain adequately accurate CFD result the following approach has been used:

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, it is the most applicable approach from the industrial point of view.

2) The Discrete Ordinates (DO) model to describe the radiative heat transfer solving thermal equations for a finite number of discrete solid angles.

3) Eddy Dissipation Concept Model (EDC) to describe the evolution of the chemical species during the combustion. The EDC approach works on the assumption that chemical reactions occur in the regions where the dissipation of turbulent energy appears, the so-called fine structures.

The features of combustion of H_2 and NG in oxygen show some important difference that must be taken into account when designing a burner that must work with both of them.

Table 1 reports the difference of the two fuels.

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

On the basis of the data reported in Table 1 the following considerations can be done

1) H_2 and NG have a comparable ignition temperature and adiabatic flame temperature.

2) H_2 ignition occurs for a wider range of fuel/oxidizer mixture than the NG.

3) H_2 flame speed is about 10 times higher than NG flame speed.

These differences imply that the H_2 requires less heat and less good mixing in order to burn than the NG.

1.1.2 CFD burner model results

CFD burner simulations have been performed to analyze the behavior of the H_2 burner and compare it to a NG burner.

The CFD results show that the increase of the H_2/NG ratio increases the maximum flame temperature and moves the maximum temperature closer to the burner tip.

The details of the various contours for the 3 MW burner with 100% H_2 have been investigated. Figure 2 shows the main characteristic of burner of 3 MW with 100% H_2.

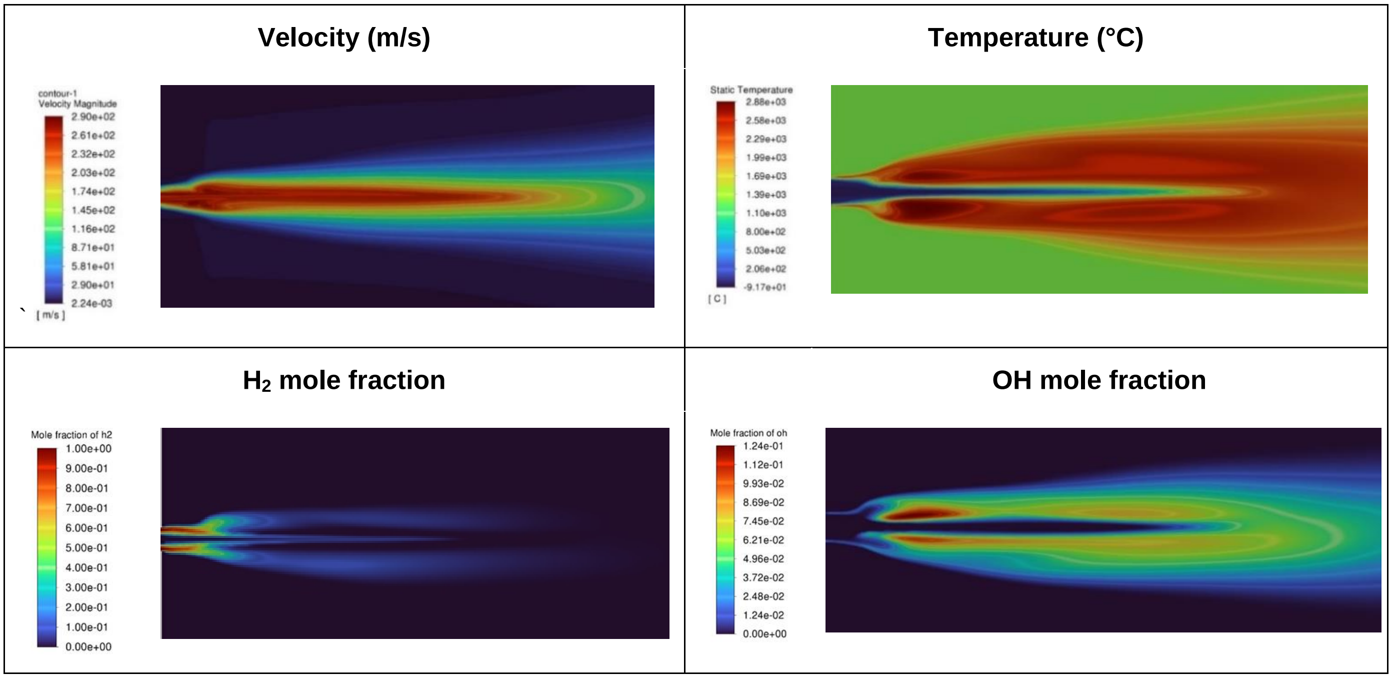

Figure 2– Characteristics of the 3 MW burner fed with 100% hydrogen

On the basis of Figure 2 the following considerations can be done:

1) The combustion of H_2 is complete in short distance.
2) The central oxygen jet remains stable, improving the stability of the flame.
3) The fast ignition favors the mixing of oxidant and oxidizer.
4) The high speed of the central oxygen permits to produce an elongated flame with a progressively combustion through the entire length of the jet.

1.1.3 Burner structure

On the basis of the CFD simulation results the burner structure has been defined. It is a monolytical structure with openings on the front face for fuel and oxygen. Central oxygen is fed with a shaped nozzle. The copper body is water cooled.

Openings for oxygen and fuel on the front copper head (including the oxygen nozzle) have been designed in order to protect the tip from clogging phenomena.

Burner comprises inlets for oxygen and fuel streams and inlet/outlet for cooling water.

Figure 3 shows the 3D overview of the burner.

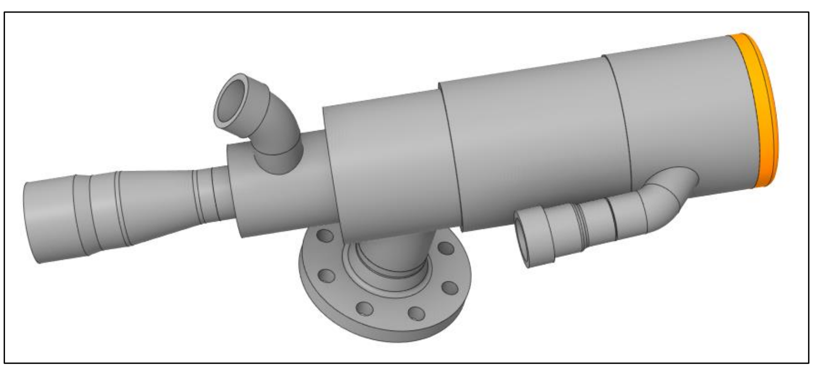

Figure 3 – ***Burner 3D structure***

3. DESIGN AND REALIZATION OF THE SYSTEM TO SUPPLY AND TO REGULATE H_2 AND NATURAL GAS MIXTURE

Nippon Gases designed and realized the hydrogen tube trailer and the Fuel Suppy Regulation System (FSRS) to mix H_2 and NG up to 100% of H_2.

The complete fuel pipeline is composed by the following main parts:

1) Hydrogen tube trailer with decompression systems.
2) Hydrogen pipeline.
3) Fuel Supply Regulation System (FSRS) to mix various percentage of H_2 and NG.
4) Flash-back arrestors system to protect the equipment from damage or explosion.

In order to respects the safety standard all the equipment are design and realized respected SIL 3 assessment.

H_2 Tube trailer with decompression systems

The hydrogen is stored inside a tube trailer made up of a semi-trailer for housing and fixing 11 tubes (2367 liters nominal ø 610 mm Length 9.700 mm) whose total geometric volume is equal to 26.000 liters at 200 barG which corresponds to 376 kg (4190 Nm^3).

The system permits to transport up to 1400 m3/h of H_2 decompressing it from 200 barG to to 10 barG by means of two redundant pressure reduction units consisting of:

1) two pressure reducers
2) four pressure gauges for visual indication of the upstream and downstream pressure
3) two safety valves for intervention in case of failure of the pressure reducer.

Hydrogen pipeline

Hydrogen could have deleterious effects on the tensile properties of metals caused by the association and movement of hydrogen with dislocations. Hydrogen-dislocation interactions modify plastic deformation processes by stabilizing microcracks, by changing the work hardening rate, and by solid solution hardening. For these reasons for hydrogen transportation stainless Steel AISI-316 is preferable for mechanical properties, welding features and corrosion resistance. Stainless steel grades (AISI-316L, -316N, -316H, -316Ti) are recommended for critical process conditions (e.g. low temperatures <253°K, high temperatures >373°K, corrosion environments). In each case also AISI-304 can be accepted for no-critical process conditions.

The maximum gas velocity allowable, to avoid erosion and embrittlement phenomena, that can be calculated by means of the following formula:

$$\boldsymbol{V = min\left[175 \cdot \left(\frac{1}{\rho}\right)^{0,43}; 60\right]} \text{ (m/s)}$$

$\boldsymbol{\rho_N}$ **=** Gas density [kg/Nm^3]

In order to guarantee the gas velocity below maximum value the following size of hydrogen pipeline have been selected:

1) DN 25 stainless steel piping for high pressure hydrogen distribution from the tube trailer to the first reduction panel.
2) DN50 stainless steel piping for medium pressure hydrogen distribution from the first reduction panel to the FSRS.
3) DN 65 stainless steel piping for low pressure fuels distribution from FSRS to hydrogen burner.

Table 2 reports the main data of the gas into the various section of the hydrogen pipeline.

Table 2 – Hydrogen pipeline data

	From tube trailer to first reduction panel	From first reduction panel to FSRS	From FSRS to the burner
Piping	1″	2″	2.1/2″
Pressure [barG]	From 200 to 30	10	5

Welded joints are recommended wherever possible but where breakable joints (threaded, flanged etc.) are considered necessary, these should be kept to a minimum since they are a potential source of hydrogen leakage. When flanged joints are used, ring joint flanges or weld-neck flanges are recommended (Ref. EN 1092-1). Compression fittings are not recommended on process lines because of the potential for hydrogen leakage.

For the weldments the following safety prescriptions must be adopted:

a) Welding shall not be performed when the temperature of the metal surface within 305 mm (12 in.) of the point of welding in all directions is lower than 16°C. The work area and surfaces to be welded shall be protected from wind and moisture conditions caused by ice, rain, snow, and running or standing water.

c) Pre-post-weld heat treatments are not required when AISI 316 is used. Refer to ASME B31.12 GR 3.5 - 3.6 for further details.

d) Peening is prohibited for all weldments, including weld metal buildup and repairs.

e) Valve end connections requiring welding, preheat or post-weld heat treatment procedures, or both shall preserve the seat tightness of the valve.

f) Thermal arc, fuel cutting, and fuel heating processes are allowed. Oxyacetylene cutting shall be restricted to carbon steel materials.

<u>Fuel Supply Regulation System (FSRS) to mix various percentage of H_2 and NG</u>

The FSRS (Fuels Supply Regulating System) control unit has the purpose of regulating the flow rate and mixing two different types of fuel (natural gas and hydrogen) to perform tests with variable gas composition and power inside the burner.

The H_2 line inside the FSRS skid is composed by the following main components:

1) Pressure reducer for bring the pressure to operating conditions, a safety valve calibrated at 5 barG
2) Pressure transmitter to monitor the pressure trend.
3) Mass flow transmitter and a pneumatic flow regulation control valves installed both low hydrogen flow rate (10-200 Nm3/h) and high hydrogen flow rate (120-1200 Nm3/h) lines.
4) Pressure gauge and a non-return valve to prevent the other fluids from returning to the line due to the pressure difference.

The FSRS is designed to be a turnkey system, therefore on a skid basis. The structure is made in 304 stainless steel square box sections to overcome corrosion-related problems and ensure continuity of the system. The electrical panel is tied to the skid so that it could be transported together and avoid having to redo the electrical connections at each site.

<u>Flash-back arrestors system to protect the equipment from damage or explosion</u>

In order to guarantee the safety standard of the steelshop the following components is installed near the burner:

1) Isolating valves: to shut off the hydrogen source in case of an emergency.
2) Flash-back arrestors: to stop the flame or reverse the flow of back gas into the equipment or supply line.
3) Non-return valves: to increase the safety in event of backfire or gas returns.

Figure 4 shows the complete hydrogen line from the tube trailer to the burner.

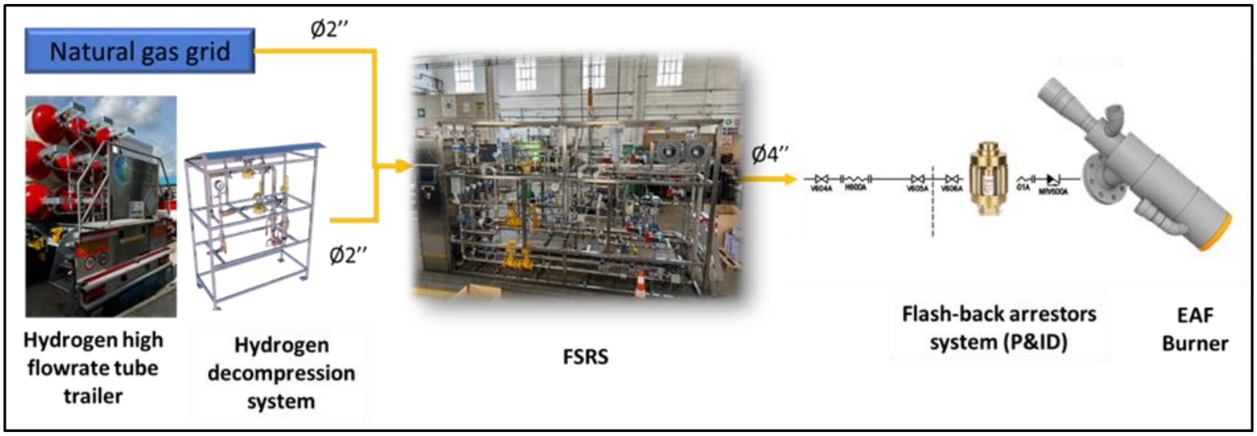

Figure 4– Main components of the hydrogen line

4. ANALYSIS THE PERFORMANCE OF HYDROGEN BURNER THROUGH EXPERIMENTAL TRIALS

In order to validate the burner performance several experimental tests both in pilot scale and industrial ones will be carried out on 2024.

<u>RINA-CSM pilot tests</u>

The RINA-CSM combustion chamber is placed at RINA-CSM laboratory in Dalmine (Italy) will be used to tests the burner performance. The combustion chamber allows to test various synthetic gaseous mixture, until 100% hydrogen with a maximum. The chamber has a section of 2x2 m with a variable length in the range of 3-7.5 m.

The combustion chamber is equipped various instruments to monitor the temperature distribution, the pressure, the flue gas flow rate and compositions (O_2, CO_2, H_2O, CO and NOx).Figure 5 shows the layout of the RINA-CSM combustion chamber.

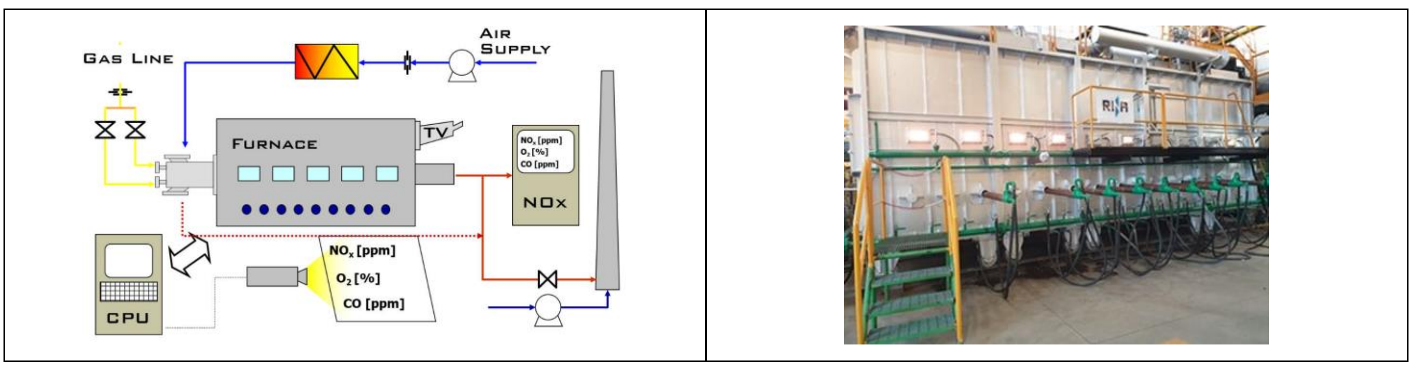

Figure 5 – Lay out and picture of the RINA-CSM combustion chamber

Experimental tests will be permitted to evaluate: thermal field, heat transfer and temperature profile in the furnace at various power input and H_2/NG mixture in order to evaluate the performances of the burner in the operation range typically adopted in EAF. Moreover, the measurement of the temperature and the composition of the flue gas will be perfored.

<u>Pilot scale EAF tests at RWTH</u>

The RWTH pilot-scale EAF is gas-tight and achieves similar operating conditions as industrial EAFs. The water-cooled furnace consists of two main components, the fixed reactor and the mobile crucible with a capacity of 40 liters and MgO-based wear lining. The operating mode is AC with two angular and vertically movable graphite electrodes.

A pilot hydrogen 50 kW burner able to work with a mixture of H2-NG up to 100% H_2 will be installed at a pilot EAF at RWTH in order to investigate the scrap melting behavior, N_2 and H_2 pick-up. The trials will be also used to investigate the off-gas composition (including NOx; O_2, H_2, CO_2,) also the change in the off-gas temperature, the overall energy balance and hydrogen pickup of the melt in an environment that includes other effects e.g. from the scrap melting. Figure 6 reports the characteristics of the pilot EAF at RWTH premises.

600kW Pilot electric Arc Furnace plant technical Data
- Transformer rated power: 850 kVA
- Secondary voltage: 250-850 V in 10 steps
- Arc current: max. 2 kA
- Active power: max. 600 kW

Water cooled furnace consisting of:
- Upper part with ring line to introduce gases and gas mixtures
- Lower part for the melting of steel scrap, non-ferrous metals and slags, movable for charging and tapping

Equipment:
- separate cooling water circuits for upper part withelectrodes and lower part with bottom electrode
- Gas supply
- Energy supply and transformers
- Off-gas system
- Control by PLC and process data acquisition

Figure 6 - Pilot electric Arc Furnace plant

Industrial experimental campaigns at FeNo and Celsa EAF

Hydrogen burner will be tested on two different EAF plants of CELSA and FENO. They have different characteristics as reported in Table 3.

Table 3 – FENO and CELSA EAF characteristics

Process Data	FENO	CELSA
Capacity (t)	147 t liquid	162 liquid
N° of burners	8 NG burners+3 sidewall lances (in the first stage burners - in the last lances)	3
Max burner power (MW)	4	3
N° of Tuyeres	3 (bottom)	3 (sidewall)
Max tuyere power (MW)	1	-
N° of Jet burners	4	1
Max Jet burner power (MW)	3	1
N°of C injectors	3	3
N°of polymers injectors	1	0
N° lime injectors	2	1
N° white slag injectors	2	-

The experimental trial concern the replacement of one burner 100% fed with NG with hybrid burners fed with hydrogen, but able to modulate the percentage of H_2-NG mixture according to EAF process stage.

Figure 7 shows the CELSA and the FENO EAF layouts.

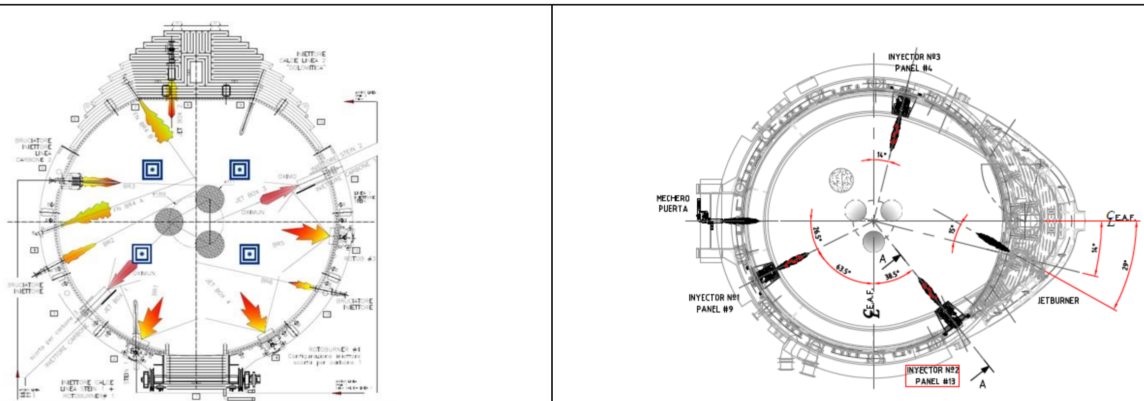

Figure 7 - FENO (right) and CELSA (left) EAFs layout

5. CONCLUSIONS

The results of CFD simulation carried out in a burner with 100% of hydrogen showed that:

1) The combustion of H_2 is complete in a few meters.
2) The central oxygen jet remains stable, improving the stability of the flame.
3) The fast ignition favors the mixing of oxidant and oxidizer.
4) The high speed of the central oxygen permits to produce an elongated flame with a progressively combustion through the entire length of the jet.

The complete fuel pipeline to deliver the hydrogen from the tube trailer to burner is composed by the following main parts:

1) Hydrogen tube trailer with decompression systems.
2) Hydrogen pipeline.
3) Fuel Supply Regulation System (FSRS) to mix various percentage of H_2 and NG.
4) Flash-back arrestors system to protect the equipment from damage or explosion.

All components are equipped with safety valves in accordance with SIL3 assessment.

For the hydrogen pipeline realization stainless Steel AISI-316 is preferable to AISI-304 due to mechanical properties, welding features and corrosion resistance. Stainless-Steel grades (AISI-316L, -316N, 316H, -316Ti) are recommended for critical process conditions but in each case also AISI-304 can be accepted for no-critical process conditions.

In order to guarantee a fine control of the hydrogen flow rate in whole working range (from 10 to 1400 Nm^3/h) the FSRS is equipped with two hydrogen lines: one for low hydrogen flow rate (10-200 Nm^3/h) and the other one for high hydrogen flow rate (120-1200 Nm^3/h).

In order to guarantee the gas velocity below maximum value the following size of hydrogen stainless steel pipeline have been selected:

1) DN 25 from the tube trailer to the first reduction panel.
2) DN50 from first reduction panel to the FSRS.
3) DN 65 from FSRS to hydrogen burner

Welded joints are recommended wherever possible but where breakable joints (threaded, flanged etc.) are considered necessary, these should be kept to a minimum since they are a potential source of hydrogen leakage. When flanged joints are used, ring joint flanges or weld-neck flanges are recommended (Ref. EN 1092-1). Compression fittings are not recommended on process lines because of the potential for hydrogen leakage.

6. ACKNOWLEDGMENTS

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