Report on H_2 combustion system optimization for direct and indirect heating

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Credits

Disclaimer

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List of abbreviations

Abbreviations	Explanation
AGA	AGA Linde
AMI	ArcelorMittal Global R&D
AMOB	ArcelorMittal Olaberria-Bergara
AMS	ArcelorMittal Sestao
CAL	Continuous annealing line
CFD	Computational fluid dynamics
CGL	Continuous galvanising line
COG	Coke oven gas
DOE	Design of experiments
LEL	Low Explosivity Value
NIP	Nippon Gases
NG	Natural gas
P&ID	Process and instrumentation diagram
PLC	Programmable logic controller
RWTH-GHI	Institute of Mineral Engineering RWTH Aachen University
RWTH-IOB	Department for Industrial Furnaces and Heat Engineering RWTH Aachen University
SAR	Sarralle
TEC	Tecnalia
WP	Work package

Introduction

Introduction

Replacement of natural gas (NG) by hydrogen as fuel is one of the key strategies that can be followed to decarbonize both indirect and direct heated combustion systems, used in reheating and heat treatment of aluminium, steel and other energy intensive processes.

A typical carbon footprint of a NG-fired reheating furnace is about 80 kg per ton of heated steel. On the one hand, energy efficiency measures would allow a reasonable reduction of both energy input and directly related emissions. It is very important to reduce the energy losses (e.g., via a better thermal insulation or waste heat recovery), or process inefficiencies (e.g., via a better regulation of the burners).

On the other hand, replacement of fossil fuels (typically natural gas), either by process off gases if available (such as coke oven gas or blast furnace gas) or by E-fuels, such as green hydrogen. In this way, this would be an alternative to a direct heating electrification. Finally, carbon capture would be an option if CO_2 can be safe stored or used (e.g., chemicals production).

One advantage of retrofitting an existing furnace to hydrogen operation is the potential reuse of infrastructure. Electrification may be an attractive option, but the revamping necessary is much more important. Therefore, industry may consider the progressive conversion to hydrogen-ready operation as an interesting strategy of fulfilling the decarbonization goals.

In addition, oxygen enrichment or oxy-combustion would allow reducing energy consumption. Also, oxygen is a by-product of the production of hydrogen by water electrolysis, so that O_2 utilization would be more attractive.

This document reports the design and the engineering of combustion system for both direct and indirect heating burners based on preliminary pilot plant tests. Also, it summarizes the inputs for the design and the integration of the hydrogen fired burner system at industrial demonstrators.

Scope

The performance of two full-scale burners, which are used in several sectors as a standard baseline, are evaluated in a pilot reheating furnace (up to 1.2 MW) in long-term 24/7 operation at AMI for H_2 and H_2/NG blends (NG as baseline). Within task 2.4, design and engineering of direct heating burners based on preliminary pilot plant tests are accomplished. The results provide input for the implementation of the demonstrators and corresponding studies in WP5/6. Also, short-term tests for design validation are conducted (Task 2.5) at a combustion chamber at TEC by SAR, NIP and AMOB.

In addition, two different radiant tube's types (W-type with plug-in recuperator, PP-type with self-recuperative burner and flameless combustion) for indirect heating applications are tested with H_2/air combustion and H_2/NG blends. Within task 2.5, design and engineering of indirect heating burners based on preliminary pilot plant tests are accomplished. The results provide input for the implementation of the demonstrators and corresponding studies in WP5/6.

Modifications from Amendment Nr. 2

Deliverable 2.5 (as stated in Grant Agreement) originally aimed to describe the results of the tests in the pilot plants of the burners for direct and indirect heating applications, paying attention to different factors as safety, emissions, temperature homogeneity or effect on materials, including also the results of the numerical simulations that will be used as inputs in WP5 and WP6.

However, the long-term demonstration at AMI semi-industrial pilot plants, originally planned in Grant Agreement as part of tasks 2.4 and 2.5, and to be reported in deliverable D2.5, are in delay due to unexpected long delivery times of components that required to reschedule all the lab activities. Since experimental trials are included as part of demonstration activities (WP6), these are therefore aligned with the scope of this WP.

For this reason, the consortium has requested to move these activities to Task 6.1 and 6.5 respectively and deliverables D6.2/6.3. This would allow for the other results of tasks 2.4 (tests with AMS burners, tests for AMOB in reheating furnace prototype at TEC, inputs for design and implementation of AMS and AMOB demonstrators as well as design of burners integration in AMI 1.2 MW combustion furnace) and 2.5 (Design of burners integration in AMI radiant tube furnace) to be reported in due time without negative effects on other WPs. Since no depending tasks are affected by this proposal, the consortium considers this rearrangement of activities suit better the project structure.

In this way, the performance of two full-scale burners will be long term evaluated in a pilot furnace (up to 1.2 MW) in long-term demonstration 24/7 operation at AMI for H_2 and H_2/NG blends (NG as baseline) in WP6. The impact of real operating conditions between 800-1400°C on safety functions (e.g. flame detection), NO_X emissions, temperature homogeneity and efficiency are evaluated. Oxygen enhanced combustion is evaluated as efficiency measure to reduce H_2-consumption in adapted air-fuel burners with the support of AGA. AMI's measurement data are used to validate RWTH-IOB's numerical simulations and to provide relevant inputs for the retrofitting actions (task 6.1). An iterative modification and optimization of the burners both by experiments and simulation is carried out by applying several primary measures to decrease NO_X emissions and adjust flame shape/length and heat release. AMI will test the effects on construction materials, refractory and coated construction elements. Samples of the material are placed in the furnace and analysed by RWTH-GHI.

On the other hand, two different radiant tubes' types (W-type with plug-in recuperator, PP-type with self-recuperative burner and flameless combustion) for indirect heating applications will be tested with H_2/air combustion and H_2/NG blends. The tests are carried out in a full-scale radiant tube pilot by AMI with a test matrix including variation of fuel composition, air ratio, furnace temperature and thermal loading. The focus in the planned tests (few weeks) besides NO_X emissions is on process stability and safety (flame detection/stability, safety functions), temperature uniformity, efficiency and emissions (CO, CO_2). In parallel, RWTH-IOB builds up corresponding numerical models to study the effect of H_2/air combustion in radiant tubes allowing an iterative experimental/numerical optimization to decrease NO_X emissions by several primary measures and enhance temperature uniformity. AMI's measurement data is used to validate RWTH-IOB's simulations. Creep simulations describing the service life of the radiant tubes will support the evaluation of applicability of H_2 for indirect heating.

Within the proposed amendment, this deliverable includes the design, and the engineering of combustion system for direct and indirect heating based on preliminary pilot plant tests. Also, it summarizes the inputs for the design and the integration of the hydrogen fired burner system at ArcelorMittal industrial demonstrators (AMS and AMOB).

Direct heating applications of hydrogen fired burners

Introduction

One way to achieve the decarbonization of reheating furnaces is to replace natural gas by green hydrogen. Figure 1 shows the impact on the carbon footprint by blending natural gas with several green hydrogen fractions, assuming the same combustion efficiencies for the sake of comparison, what is a reasonable assumption in case of air-firing. It can be observed that there is no linear relation with the volumetric fraction, due to the differences in heating value of both fuels. Therefore, higher H2 volumes are necessary to achieve a substantial carbon footprint reduction. That is, blending 50%-vol. green hydrogen allows cutting carbon footprint by about 20%, and to cut carbon footprint by more than 50%, about 80%-vol. green hydrogen blends are necessary.

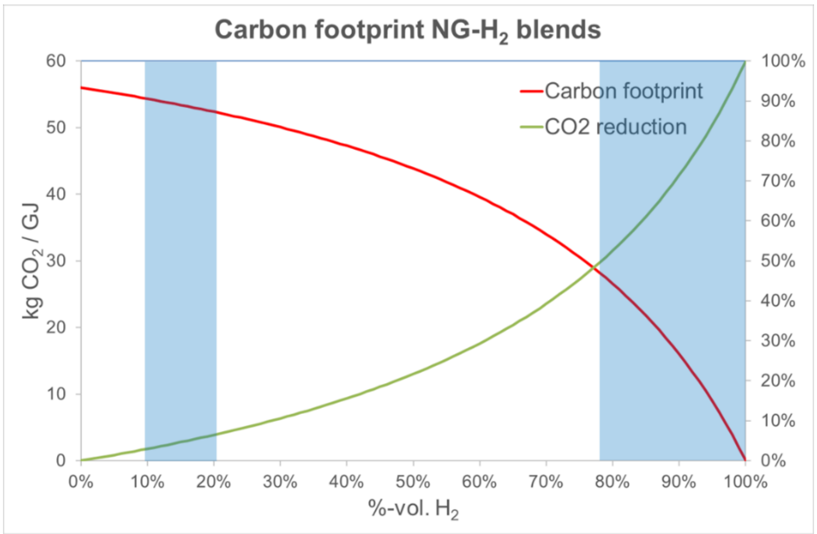


Figure 1. Carbon footprint of hydrogen-natural gas blends.

Two areas have been highlighted in blue. On the left, the range 10-20%-vol. H_2, as the limit for hydrogen, claimed by several burners manufactures, that would allow using the existing equipment. The impact on carbon footprint would be lower than 10%. The second region corresponds to large hydrogen volumes, that would allow substantial carbon footprint reduction (higher than 50%). In this case, there would be a very negative impact on NO_X emissions, what would make not regulation compliance the use of conventional burners. State-of-the art best-available technologies, such as flameless combustion, would be necessary to remain at low NO_X levels with high hydrogen fractions.

Different types of direct fired burners are installed in reheating furnaces:

1. Jet-flame burners, installed in sidewalls or frontal walls
2. Flat-flame burners, installed in roof

Spite oxyfuel would be the most efficient combustion process, in addition to the potential availability of oxygen in case hydrogen is produced locally by a electrolyzer, the state-of-the-art burner typologies are mainly based on preheated air. Most large furnaces have a recuperator installed in the main waste gases duct, whereas smaller tunnel furnaces or heat treatment furnaces use high efficiency self-recuperative burners. In a number of plants, regenerative burners allow higher preheated air temperatures.

Design and engineering of direct heating burners

Several practical aspects and key points of firing hydrogen in furnaces are presented. Firing of hydrogen is technically feasible but not straightforward. There is a potential impact on the material (e.g. heat transfer rate, flue gas atmosphere), on the furnace integrity itself (e.g. refractory material) and on the pollutants emissions (NO_X), that shall not be underestimated.

Safety considerations

In relation to handling hydrogen, it is important to take into account that it is an odorless, colorless and tasteless gas. That means, for combustion applications it would be important to add odorants as it is done with natural gas (mercaptans). Its high diffusivity makes storage difficult. It would be suggested to rinse piping with nitrogen in case of consumption shut-down (this is a good practice, used in reheating furnaces with other fuel gases).

Since it is very light, it would be required to place hydrogen detectors in the ceiling indoors. In case of a leakage outdoors, it would be quickly dispersed. A very important characteristic is that it is extremely flammable, and flame is pale. Combining it with a low radiant heat fire, it would make fires difficult to be detected with to the human senses.

Hydrogen presents wide flammability limits. That is an advantage in terms of flame stability, but hazard is increased in case of leakage (a 4%-vol. H2 to ~75% by volume in air is flammable at room temperature). Furthermore, flame velocity is about 10 times higher than natural gas. That makes hydrogen more susceptible to flashback, requiring higher injection velocities (pressures). For most of the practical industrial burners (non-premixed flame), flames generated will be shorter and more intense. That would make necessary to take into account a proper design of gas injector (lance/nozzle) and the refractory of the air diffusor and burner block.

Flame luminosity is less intense than when firing natural gas. That could require specific designs for flame monitoring sensors, and it is a point to be consider in the heat transfer mechanism.

A specific hazard risk analysis shall be addressed to handle hydrogen and to design hydrogen supply networks, pressure reduction stations and metering/regulation trains.

Heat release, combustion efficiency, and NO_X emissions

Adiabatic flame temperature is higher than natural gas. This allows a higher combustion efficiency but increases the potential to emit higher NO_X levels. Hydrogen combustion presents higher reactivity for NO_X generation due to the higher flame temperature and the faster mixing with oxidizer. That makes necessary to use low NO_X burners for high hydrogen fractions (e.g. enhancing flues recirculation).

Using existing air-burners, the hydrogen fraction in the fuel gas would be limited. Only adapted low-NO_X burners would allow firing 100% hydrogen or flexible mixtures NG-H_2.

Another important point to be consider is how to present the NO_X emission figures. Currently the European regulation establishes a dry-flues concentration basis (i.e. mg NO_X per Nm^3 of dry-flue gases referenced at 3% oxygen). In other countries, a heat release basis (g/GJ) is used. That seems to be more rational for hydrogen firing (higher water fraction than in case of NG). And should be at any case consider by oxy-firing, since water vapor would represent about 98-99% of the flue gases (1-2% O_2). Anyway, it would be interesting to use a production or hourly base (i.e., g/t_steel or kg/h), so that energy efficiency measures are not penalized.

The points highlighted herein above regarding flame temperature and flame velocity implies a different flame geometry in a certain burner, comparing NG and H_2 firing. Also, the heat release pattern is modified. Shorter and more intense flames would change the temperature uniformity/pattern in the furnace atmosphere, refractory walls and steel load. On the other hand, the higher fraction of water vapour makes the radiative contribution of the products of combustion higher. Furthermore, for a certain flues' temperature, hydrogen combustion efficiency is higher (or higher temperatures can be achieved for a certain heat release).

Two main implications arise. First, the burner should be rightly design, to achieve a proper flame geometry and heat transfer pattern. Finally, the steel reheating curve should be modelled to define new temperature set-points (or thermal power inputs). The impact on oxidation (yield, morphology) and decarburization should be also evaluated.

Due to the high cost of green hydrogen, it is very important to maximize the combustion efficiency. In this way, high temperature air preheating (e.g. regenerative burners) or oxygen enhanced combustion are two high potential technologies.

Retrofitting capabilities of reheating furnaces

From the point of view of the engineering combustion characteristics, it seems feasible the adaptation of an existing natural gas fired installation to a flexible natural gas – hydrogen operation.

As shown in Figure 2, for a unit power and based on the lower heating value, the required equivalent fuel (based on its Wobbe index) would differ not so much, thanks to the lower density of hydrogen. Indeed, the current operation of some furnaces already allow switching between NG and COG with the same conventional burners (without dual-fuel lances). Furthermore, the required combustion air flow and the generated flues flow will be lower than by NG firing. That will allow keeping the existing air fans as well as the exhaust gas system (waste gases duct, stack, recuperator, exhauster fan, etc.).

On the other hand, oxy-firing presents higher complexity for retrofitting. First, air is not used as oxidizer, but oxygen. No air fan or air recuperator is needed. Also, the flues volume generated is much lower. Attention should be paid to possible undesired water condensation. A big revamping would be required for fully conversion to oxy-firing.

A compromise solution may be the implementation of oxy-lancing technology. This is executed externally to the burner and would allow increasing the oxygen fraction in the oxidizer up to 50-60% without replacing the burners. Furnace throughput can be increased, or fuel consumption can be reduced. References claim between 10-30%. Oxygen boosting can be applied in a flexible way (on demand).

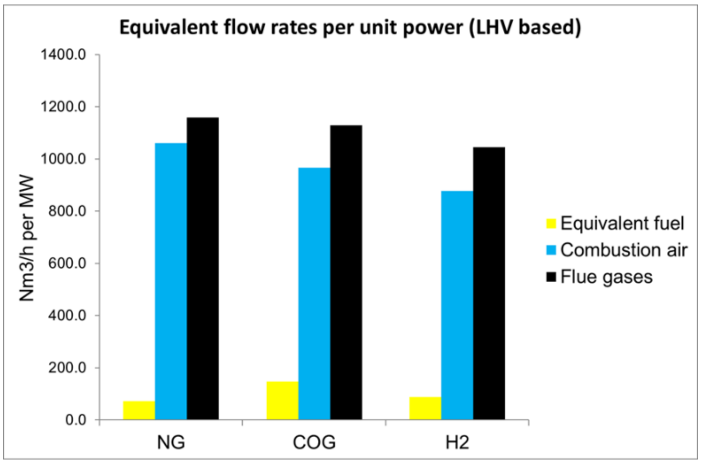


Figure 2. Equivalent flow rates per unit power (NG, COG, H_2).

Experimental campaign set up

With the goal of evaluating the performance of full-scale industrial burners, which are used in several sectors as a standard baseline, long-tests in a pilot reheating furnace (up to 1.2 MW) with 24/7 operation at AMI are executed. Using natural gas as baseline, H_2 and H_2/NG blends are tested under different operating conditions. The results of this experimental campaign provide input for the implementation of the demonstrators and corresponding studies.

Combustion furnace

A 1.2 MW combustion plant operated by AMI and located in ArcelorMittal Asturias plant is interconnected to the natural gas and process off-gases networks (coke oven gas and blast furnace gas) that feed the hot rolling mill reheating furnaces. In Figure 3 is represented a three-dimensional layout of the facility, and in Figure 4 is shown picture of the combustion chamber.

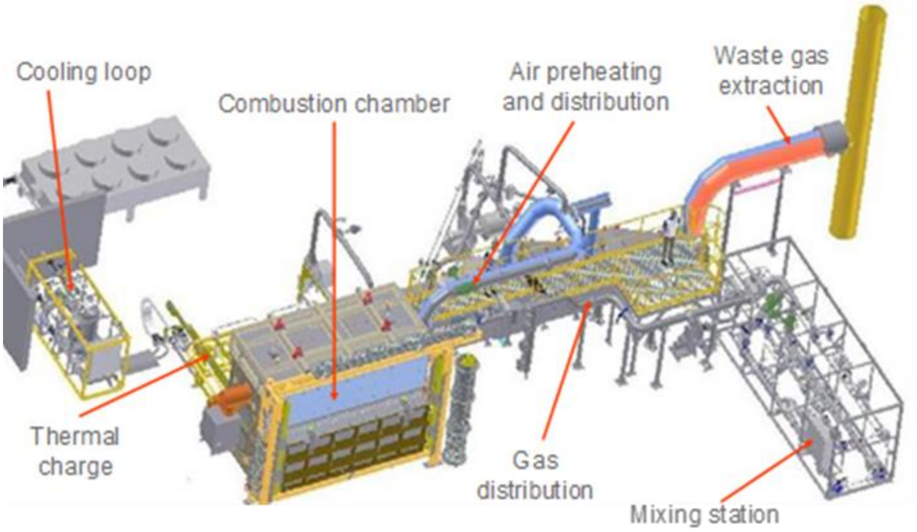


Figure 3. AMI direct furnace testing facility layout.

As a first step, gases are fed to a mixing, metering and pressure/flow regulation station. Pressure regulation valves, flow rate regulation valves, flow meters (orifice plates), and safety devices (shut-off valves and pressure switches) are installed. Mix gas is then boosted and flowed to the burners, where flow rate is measured and regulated. A mass spectrometer is available to analyse the mix gas composition. Safety shut-off valves (tightness control system), ultraviolet main flame detection and pilot burners are also installed. On the other side air is blown and preheated in a central air recuperator. Oxygen can be injected either in the combustion air pipe or in the burner itself (oxyfuel or oxy-lancing technology). Pressure switches, flow rate regulation valve, flow meter and temperature sensors are installed.

Combustion is made in a 4.6x1.5x2.8 m combustion chamber, where temperature and oxygen level are measured. A low NO_X dual-fuel burner has been installed for the commissioning and first long-term tests. Waste gases are flown by means of an exhauster fan, preheating the combustion air. Combustion air temperature can be regulated by means of a recuperator by-pass regulation valve. NO_X, level, carbon monoxide, carbon dioxide, and oxygen, can be measured in the waste gases duct.

A thermal charge consisting of six water lances is used to remove heating power from the combustion chamber. Water flow is regulated and measured, in addition to the temperature difference between furnace inlet and outlet. Water temperature is then regulated by means of a dry-cooler, completing the close-loop circuit.

Figure 4. AMI direct furnace testing facility.

Hydrogen supply

The industrial pilot plant has been equipped with a decompression unit, able to connect two semi-trailers containing 720 kg of hydrogen (24 MWh, enough for one-day operation). Hydrogen is regulated at 4 bar and a pipe connects the hydrogen supply facility with the combustion chamber mixing station, so that the furnace can fire different blends of natural gas and hydrogen.

Figure 5. Hydrogen supply and decompression station at AMI.

Two shut-off valves in serial, located outdoors, allow insulating the hydrogen supply in case of failure of any interlock (e.g., gas detection inside the building). Pipeline can be rinsed with nitrogen, that is also used for tightness control.

Burner integration in furnace

The burners are installed in the furnace using a steel plate, so that the burner refractory suits the furnace inner wall, as shown in Figure 6. The burner is instrumented to collect main performance data.

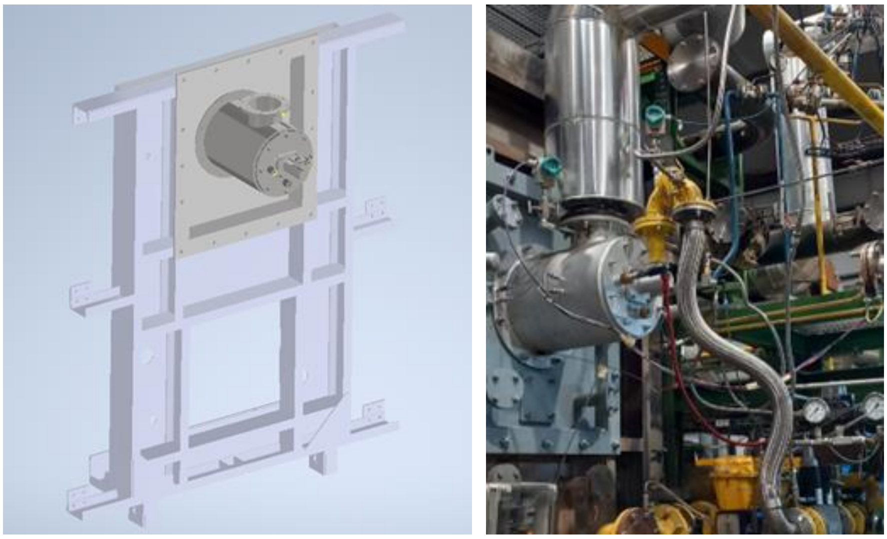


Figure 6. Burner integration at AMI furnace.

Figure 7 shows the general process an instrumentation diagram for a furnace, able to fire natural gas and hydrogen blends. A mixing station can blend both gases in different fractions. For this purpose, flow meters and control valves are used. Pipelines and metering/regulation devices should be sized accordingly to the maximum and minimum flow rates. In a similar way, air blower and an oxygen enrichment line are installed, with its respective metering/regulation devices. Air is preheated in a central recuperator.

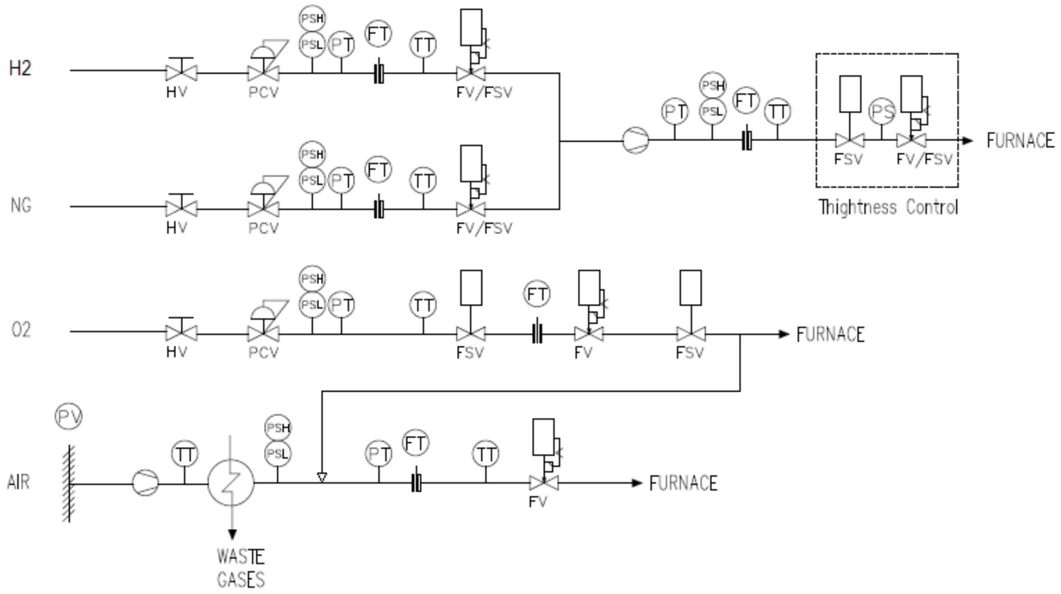


Figure 7. Process diagram for direct heated air/oxygen/fuel integration.

Safety devices are required to comply the European and ISO regulation (UNE-EN ISO 13577). This standard deal with significant hazards, hazardous situations and events relevant to combustion and fuel handling systems, covering fuel pipework, burner system, ignition device and safety related control system (protective system). Pressure switches, temperature switches, flow switches, air-to-fuel ratio control and flame detection (burner control unit) acts directly to the tightness control system (safety shut-off valves), as Figure 8 shows. This burner control unit monitor and control the ignition device (e.g. pilot burner) and/or the main burner flame, at least when furnace temperature remains below 750°C.

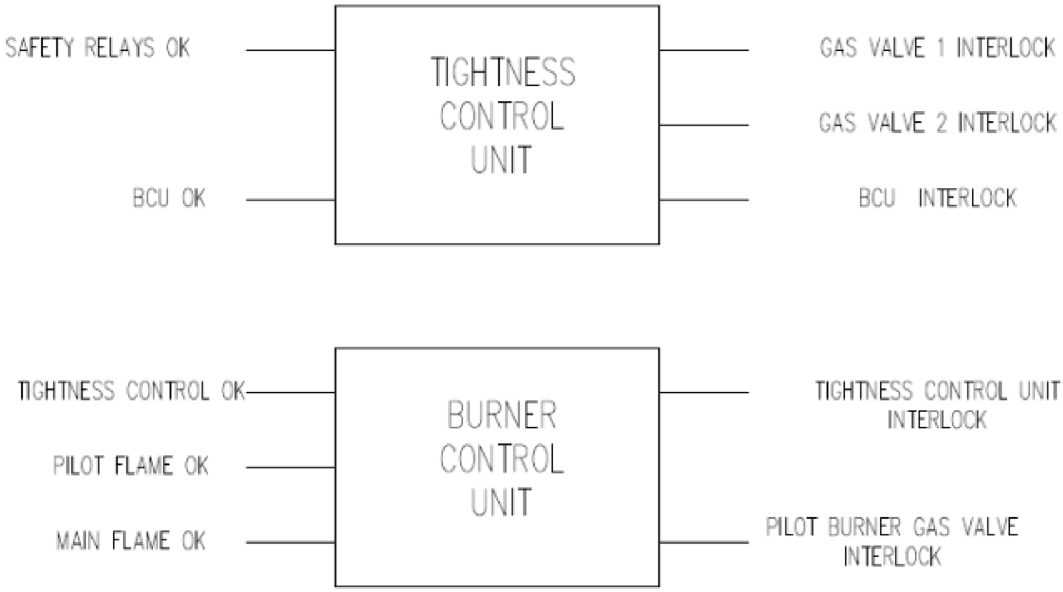


Figure 8. Safety logic schema.

Experimental set-up of experiments

Different NG/H2 blends are fired and compared with a standard operation of coke oven gas (COG). COG contains already about 60% of hydrogen in its composition. The goal is evaluating the potential replacement of fossil fuel in direct heated furnaces, assessing both combustion efficiency, heat transfer profile and emissions. Also, oxygen will be used in existing burners (via air enrichment of oxylancing).

Long term-testing has been carried out at different furnace conditions (Figure 9), comparing a reference scenario with different replacement rates by hydrogen. Several gas mixtures are therefore tested to assess heating efficiency.

Figure 9. Long-term testing AMI direct heated combustion chamber.

The methodology consists of establishing an energy balance, by measuring the energy transferred to the thermal load, comparing different technologies, gas mixtures and furnace conditions. That is the usable energy that can be compared with the supplied by the fuel (heating value). Since each reheating furnace has its own energy losses (e.g., walls) and recuperator effectiveness, it is important to normalize the efficiency for a certain condition. Figure 10 shows a Sankey diagram of the furnace. Enthalpy of both oxidizer and fuel streams is first calculated, based on the composition and temperature. Then heat power to thermal charge and waste gases losses are calculated based on the water flow and waste gases enthalpies (composition and temperature). Finally heat balance is closed with the heat losses through walls, validated by thermographic inspections.

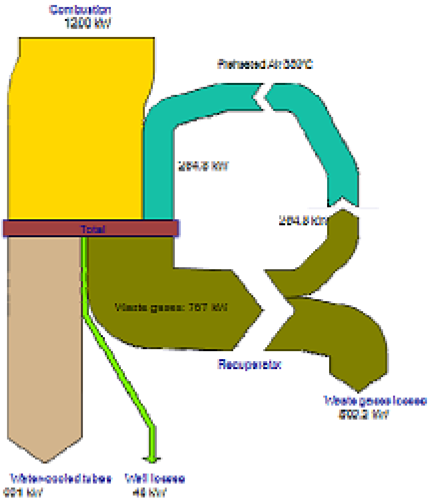


Figure 10. Sankey diagram of the AMI direct furnace.

Inputs for design the integration at ArcelorMittal industrial demonstrators

ArcelorMittal Sestao (AMS) hot rolling mill plant is linked to the electric arc furnaces by two tunnel furnaces directly fed by the continuous casting lines. The biggest NG consumer of the plant is the tunnel furnace itself, heated by high-efficiency self-recuperative burners.

The goal of this study is to evaluate the operation of the tunnel furnace burners with hydrogen and NG-H_2 blends, as a straightforward alternative to decarbonize plant. Considering the large number of burners, a first analysis aims to assess the capability of replacing / adapting these burners to hydrogen operation.

Cold air is injected and preheated in a recuperator installed in each burner, achieving high efficiency. With this configuration, the whole flue gas flow is exhausted through the burners. Therefore, there is no central flue gas exit, making more complex the usage of other technologies like oxy-fuel burners. At high temperature operation in the furnace, the burners work in the called “FLOX” mode, that is, a low NO_X mode achieved by the high turbulence injection of gas that allows lowering the peak flame temperature and therefore the related thermal NO_X emissions. Two types of burners are installed in each tunnel furnace: FLOX burners, only used at high temperature operation, and FLAME-FLOX burners, allowing to be operated at low temperature (below 850°C, conventional mode FLAME, not FLOX) and therefore used to heat-up the furnace.

A testing campaign in the combustion pilot furnace of AMI was carried out to characterize the burners operation, aiming to verify the burner design, assess burner performance, and to validate CFD models with experimental data. Four 240 kW burners have been installed in the reheating furnace 1.2 MW AMI combustion furnace, at both sidewalls (top and bottom heating). The same fibre material as used in Sestao (Figure 11) has been installed in the windows made to locate the four burners. Moreover, in order to evaluate the impact of the flame directly on the tunnel furnace walls, some blocks have been placed in front of the burners.

Figure 11. Sestao burners integration at AMI furnace for preliminary trials.

During the commissioning of the burners, it was necessary to adapt both air and gas supply. Natural gas flow per burner is 24 Nm3/h, whereas hydrogen is 80 Nm3/h. A manual adjustment of the gas orifice has been done to allow the required hydrogen flow, whereas natural gas pressure is slightly reduced. In this way, it has been possible to fire in a flexible way natural gas, hydrogen and different blends.

In a similar way, the air orifice has been adjusted to the required flow in natural gas operation. Since the required air flow per thermal power unit is lower when firing hydrogen, in order to avoid excess air operation (and therefore higher scale losses and NO_X emissions) it is suggested to regulate the air input, e.g. with a variable speed drive or a control valve. In the same way, flue gas exhaust is lower. To keep furnace pressure in slightly positive overpressure values, it is recommended to regulate the exhaust driver, via variable speed drive or a motorized damper.

Figure 12 shows a right burner adjustment, for a jet-flame during the burner start-up, for both NG (left) and hydrogen operation (right). One of the four burners have been fully instrumented, to monitor flue gas temperature and composition (CO_2, CO, O_2, NOX, SO_2). At high temperature operation (> 850°C), the burner can switch to the low NO_X mode

Figure 12. Burner start up with NG (left) and H_2 (right)..

A long-term testing campaign was carried out at AMI at AMI 1.2 MW pilot reheating furnace with 4 burners. Furnace temperature was maintained between 1150 and 1180°C, according to the heating profile of the slabs in the tunnel furnace (Figure 13). Although different excess air levels have been considered, operation at 1% O_2 in flues can be assured without generation of unburnt fuel.

Figure 13. Flameless operation at operating temperature with hydrogen.

From the long-term testing campaign, it can be concluded that the existing burners installed in Sestao tunnel furnace are able to fire hydrogen as well as blends with natural gas, keeping the performance in terms of heat transfer, and working below the 400 mg/Nm^3 emission limit, spite the increase when firing hydrogen in comparison of natural gas (aligned with CFD modelling results).

It follows a set of recommendations for the industrialization of the system. The engineering of this system is part of the WP6, in which a demonstration campaign will be executed in Sestao tunnel furnace for 16 burners.

Burners:

1. Installation of double gas shut-off valve (both FLAME and FLOX). Currently there is only one shut-off valve. This double valve can be actuated by one command wire, so that the existing installation is kept.

2. Installation of ultraviolet flame detector in FLAME-FLOX burners, necessary for hydrogen flame supervision. It would allow also to supervise flame in FLOX operation.
3. Installation of ignition transformer in FLAME-FLOX burners. Instead of a portable ignitor, a fixed ignition system would allow automated burner start-up.
4. Review of burner control system. It is necessary to integrate flame supervision, ignition system and furnace temperature safety interlocks.
5. Use nitrogen instead of air for the gas lance purging system (due to the risk of flashback).

Gas/air distribution:

1. For 100% NG or 100% H2 operation in each regulation zone, it is necessary to install a hydrogen pressure reducing station, connected to the natural gas regulated line.
2. Since the air demand would be reduced when hydrogen is fired, a variable speed drive in each combustion air fan would allow regulating the excess air.
3. It is recommended to be able to regulate exhaust system (either with a variable speed drive or with motorized control valves).

Burners' instrumentation:

1. It is recommended to check flues and preheated air temperature in all burners (preventive maintenance), as well as oxygen, carbon monoxide and NO_X emission level in exhaust.
2. It is recommended to install different measurement points of oxygen level in the tunnel furnace atmosphere.

Conclusions and next steps

Main conclusions are summarized here below:

- Dedicated revamping in the pilot plant to be able to use new burner units with hydrogen as fuel and NG/H_2 blends was studied and completed.
- The burner integration has been designed to cope with new requirements in terms of safety and process. Special attention has been paid to determine the interlocks that should be added to the semi-industrial pilot plant furnace.
- As a result, all the needs and modifications have been listed and executed in the pilot plant to be able to start with the tests.
- Sestao tunnel furnace revamping considerations (for the natural gas baseline) has been also defined, for the industrial site demonstrations.

Short-term test at a combustion chamber at TECNALIA with material from AMOB

Introduction

Switching from the current NG-air combustion to oxy-combustion of both NG and H_2 in reheating furnaces is a major challenge for steelmakers. One of the biggest concerns is the effect that changing the combustion atmosphere may have on the steel. It is assumed that changing the oxidiser from air to oxygen generates a more oxidising atmosphere, which will presumably have a negative effect on the weight loss suffered by the steel in these furnaces. In addition, the effect of the water vapour generated after the combustion of H_2 is still a subject to be studied.

Therefore, in this work, a study was carried out on the weight loss suffered by a structural steel, supplied by ArcelorMittal Olaberria-Bergara (AMOB) (Gipuzkoa, Spain), after the application of a heating as close as possible to the industrial one in a combustion chamber located in TECNALIA's facilities (Irun, Gipuzkoa, Spain). The combustions to be studied will be NG-air (ref. condition), NG-O_2 and H_2-O_2.

Materials and experimental procedures

Steel

The material selected for this work was a 400 mm long structural S355JR steel supplied by AMOB. Figure 14 shows the dimensions of this material.

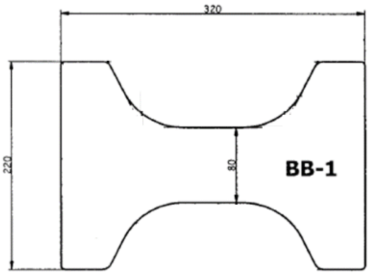


Figure 14. Dimensions of the structural steel used in this work.

Facilities

In Figure 15 a general view of the facilities can be seen.

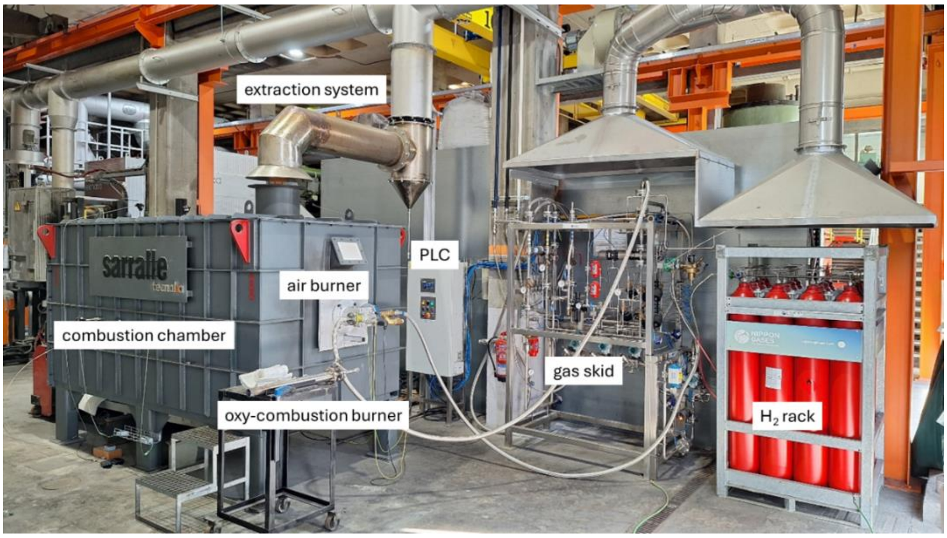


Figure 15. General view of the facilities. Including the combustion chamber, gas skid, PLC, H_2 rack, extraction system, and air and oxy-combustion burners.

Combustion chamber

The combustion chamber, manufactured by SARRALLE, has an internal cavity measuring 2700 mm (L) × 850 mm (W) × 850 mm (H) and is lined with 300 mm of refractory material. The burner is installed on one side of the chamber, while a door on the opposite side allows for the insertion of the material to be treated. The chamber is equipped with several multi-purpose ports, enabling the insertion of various probes such as thermocouples or pressure sensors. The gas outlet, located at the top near the burner wall, has an internal diameter of 140 mm.

Gas skid + programmable logic controller (PLC)

The gas skid was manufactured by NIPPON GASES. It is design to operate with H_2, NG, or blends of both as fuel, and oxygen or air as oxidiser. The current configuration supports operation within a power range of 35 kW and 180 kW.

The skid is connected to a PLC, which enables three operational modes:

- Constant power setting.
- Target holding temperature.
- Controlled heating rates.

Burners

Two burners were employed in this study:

- Oxy-combustion burner: A 150 kW burner manufactured by SARRALLE, capable of operating at up to 300% of its nominal power.
- Air-combustion burner: A 230 kW burner, commercialised by Kromschroeder, with the capability for oxygen enrichment.

Gas supplies

- Oxygen: Supplied in liquid phase by NIPPON GASES and stored in a dedicated tank. Connection to the skid is via pipeline.
- NG: Supplied directly from the natural gas network via pipeline.
- H_2: Supplied by NIPPON GASES in racks of 16 bottles at 200 bar, connected to the skid via hose.
- Compressed air: Provided by an on-site compressor and delivered to the skid through piping.

Heat treatments

The heat treatment procedures aimed to replicate the industrial thermal cycle applied to structural steel in the AMOB reheating furnace, which reaches 1200 °C in 70 minutes—the time required for the material to walk through the entire furnace. A detailed description of this furnace is available in Deliverable 2.4 of this project.

As Work Package 6 (WP6) involves retrofitting a section of the furnace from NG-air to H_2-O_2 combustion, this study evaluated the material response under the following combustion conditions:

- NG-air combustion (reference condition).
- NG-O_2 combustion (intermediate step in case of H_2 supply limitations).
- H_2-O_2 combustion.

Set-up

Before conducting the heat treatments, a preliminary set-up phase was necessary. This involved:

- Equipping the combustion chamber with various probes.
- Configuring the PLC to replicate industrial thermal cycles as closely as possible.

Combustion Chamber and other facilities

Several Type S thermocouples with ceramic protective sheaths were installed at strategic points within the combustion chamber to monitor temperature distribution. In total, six thermocouples were placed: two on each side wall, one on the vault, and one at the gas outlet. The thermocouples on one side wall, the vault, and the gas outlet were inserted approximately 50 mm from the refractory lining, while those on the opposite side were placed 335 mm away, to avoid direct flame contact. These thermocouples are rated for temperatures up to 1750 °C, but only for short durations.

The extraction system at TECNALIA's facilities is a general-purpose system and it is not specifically designed for the combustion chamber's exhaust gases. As shown in Figure 15, the extraction system is not directly connected to the chamber's gas outlet, leaving a gap between them. Even at minimum extraction power, it was suspected that could be a negative pressure inside the chamber during oxy-combustion, potentially drawing in ambient air and disrupting flame stability.

To address this, two differential pressure transmitters were installed (see Figure 3). Measurements confirmed that under oxy-combustion conditions, the chamber experienced negative pressure. This issue was solved by reducing the outlet gas section, thereby stabilizing internal pressure and ensuring proper flame development.

Figure 16. Combustion chamber with the differential pressure transmitters.

Another important aspect was to ensure that the atmosphere generated inside the combustion chamber corresponded to the intended conditions. Given that the main objective of this study was to analyse the oxidising effect of different combustion atmospheres on the material, it was essential to measure the residual oxygen concentration inside the chamber.

To this end, a lambda probe was used. The probe was installed in a small measurement cell located above the combustion chamber (Figure 17). This cell included:

- A sampling pipe inserted into the combustion chamber, reaching approximately 10 mm above the inner refractory wall, directly above the area where the material is placed during testing.
- A welded cooling coil, which served to cool the extracted gases before they reached the suction device used to suck the gas sample.

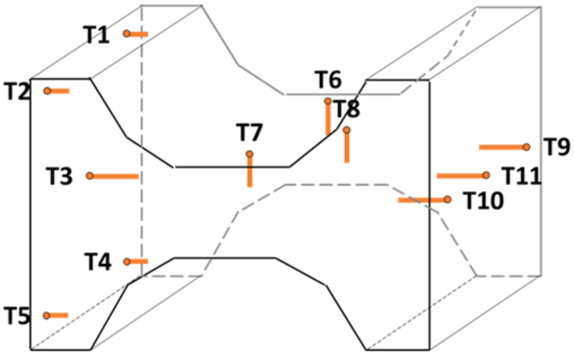
This configuration allowed for accurate monitoring of the oxygen content in the combustion atmosphere, providing key data for evaluating the oxidising potential under each combustion condition.

Figure 17. Lambda probe measuring assembly.

Material and heat treatments

Due to the dimensions of the sample, a certain degree of temperature heterogeneity was expected at different depths. Additionally, the configuration of the combustion chamber, with a single burner located at one end, suggested that temperature gradients would likely develop between the burner-facing side (burner face) and the side closest to the door (front face).

To characterise this thermal behaviour, the first trial was conducted using 11 thermocouples strategically placed at various lengths and depths within the sample. This arrangement allowed for a detailed assessment of the internal temperature distribution during the heat treatment process (Figure 18 and Figure 19).



Thermocouple	Depth (mm)	Distance to front face (mm)
T1	25	350
T2	25	50
T3	55	200
T4	25	350
T5	25	50
T6	40	350
T7	40	50
T8	40	200
T9	55	350
T10	55	50
T11	55	200

Figure 18. Schematic representation of the placement of the thermocouples in the sample for the first set-up trial.

Figure 19. Structural steel sample with 11 thermocouples inside the combustion chamber.

This first trial was conducted under NG-air combustion conditions and involved heating the sample from room temperature simultaneously with the combustion chamber. The two main objectives of this test were:

- To verify that all thermocouples reached 1200 °C.
- To identify the most relevant monitoring zones for subsequent trials.

To achieve this, the combustion chamber was heated to 1250 °C and maintained at that temperature for approximately 30 minutes. The thermal profiles recorded by the 11 thermocouples throughout the trial are shown in Figure 20.

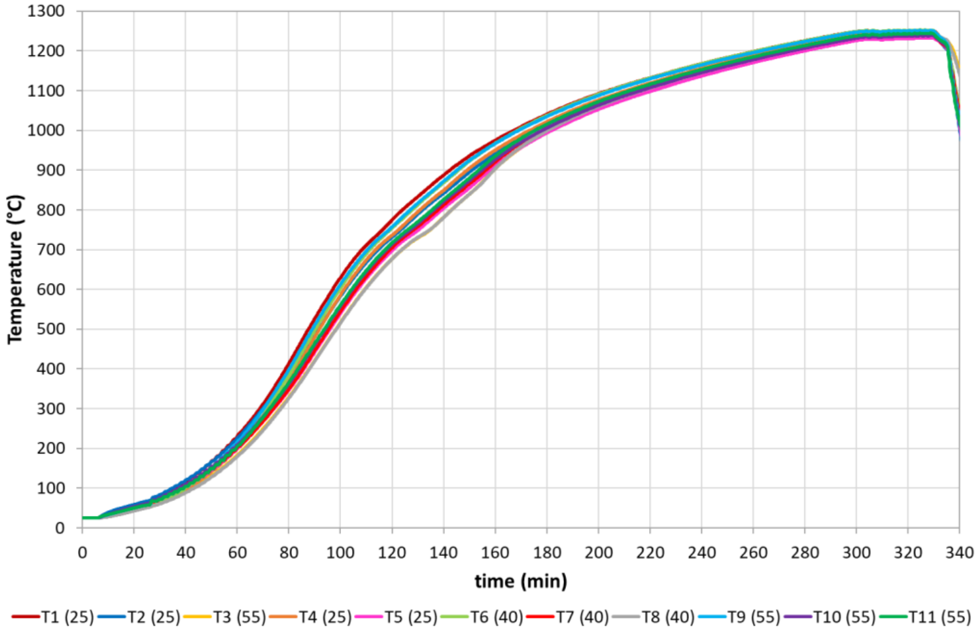


Figure 20. Thermal cycle of the 11 thermocouples throughout the first trial. The number in brackets refers to the depth of the thermocouple.

Figure 21 provides a detailed view of the time at which each thermocouple reached 1200 °C. The last thermocouple to reach this temperature was T5 (located at the bottom, front face, 25 mm depth). At that moment, the maximum temperature difference between T5 and the hottest thermocouples (T1 and T6, both on the burner face) was 25 °C. The time lag between the first and last thermocouples reaching 1200 °C was 19 minutes.

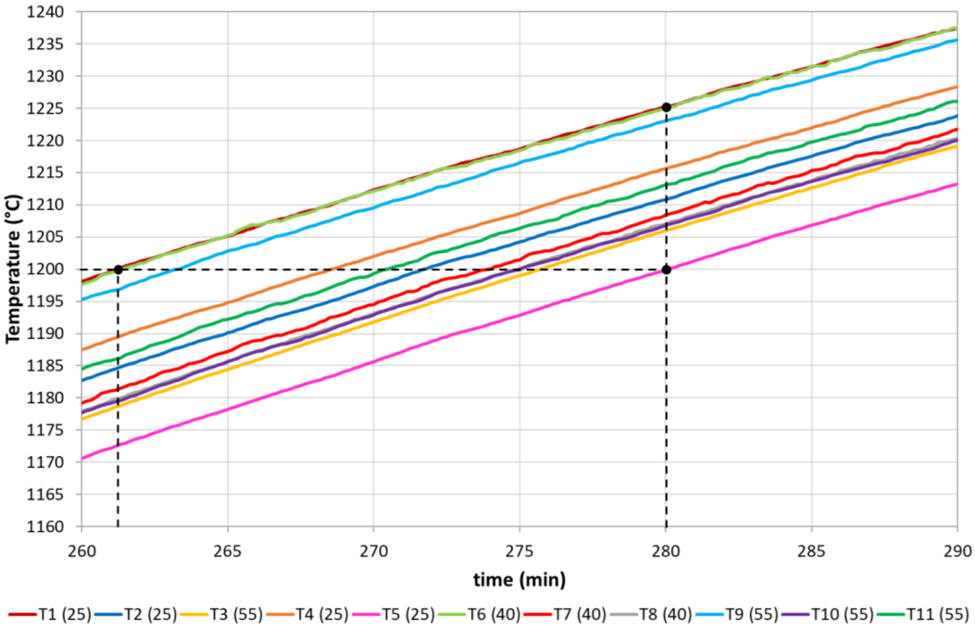


Figure 21. A detailed view of the time at which each of the thermocouples reached 1200 °C.

At the end of the trial, once the chamber temperature had stabilised, the thermocouples showed three distinct temperature zones, as illustrated in Figure 22:

- 1250–1251 °C: Thermocouples located on the burner face (T1, T6, and T9), except for the one at the bottom (T4). These readings were fully stabilised and aligned with the chamber setpoint.
- 1232 °C: Thermocouple T5 (bottom-front). The temperature was still increasing at a rate of +2 °C over the last 10 minutes.
- 1238–1244 °C: All remaining thermocouples (T2, T3, T4, T7, T8, T10, and T11). These also showed a slight upward trend, with an increase of +1 °C in the last 10 minutes.

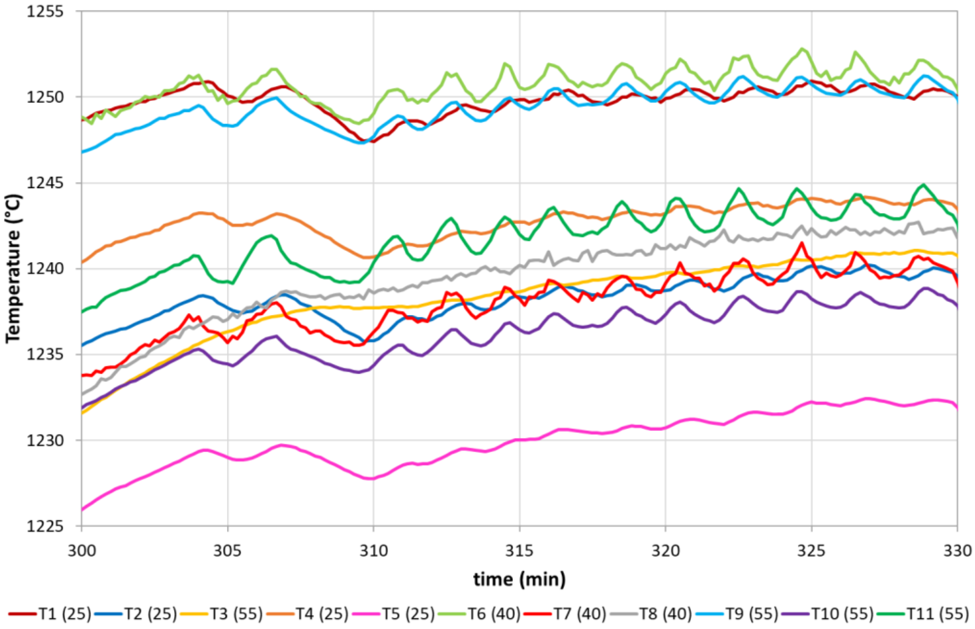


Figure 22. Final stage of the first trial with the combustion chamber temperature stabilized.

Once it was confirmed that all points of the sample could reach 1200 °C, a second phase of set-up trials was carried out.

In the following set-up trials, the objective was to define a thermal cycle within the combustion chamber capable of heating the sample to 1200 °C in 70 minutes. Unlike the initial test, in this case the combustion chamber was preheated before the sample was introduced.

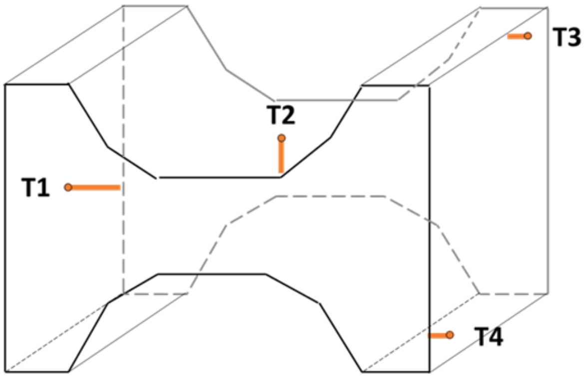
For safety reasons, the number of thermocouples was limited to a maximum of four. The selected thermocouples, as shown in Figure 23, were chosen to ensure coverage of:

- Both left and right sides of the sample
- Burner-facing and front-facing sides
- Top, centre, and bottom positions
- Depths of 25 mm, 40 mm, and 55 mm

This configuration also retained thermocouples with critical thermal behaviour:

- T3, which had previously shown a tendency to exceed the target temperature, and
- T4, which had shown a tendency to fall short of the target.

Additionally, T1 and T2, located in the central region of the sample, were included to monitor the core temperature evolution.



Thermocouple	Depth (mm)	Distance to front face (mm)
T1	55	200
T2	40	200
T3	25	350
T4	25	50

Figure 23. Schematic representation of the thermocouples selected for the trials.

Although the combustion chamber was preheated prior to each trial, opening the door to load the sample caused a temporary temperature drop. Therefore, it was necessary to define a heating rate that would allow the system to recover and ensure that the sample reached 1200 °C by the end of the 70-minute cycle.

To address this, a methodology was established, which is illustrated schematically in Figure 24. The approach involved programming the PLC with a controlled heating ramp that compensated for the initial temperature loss and ensured the desired thermal profile.

It was anticipated that NG-air combustion would represent the most challenging scenario, as achieving high heating rates is generally more difficult compared to oxy-combustion, even when using the same burner power. For this reason, the initial trials were conducted under NG-air conditions and subsequently replicated using oxy-combustion to validate the methodology under more favourable conditions.

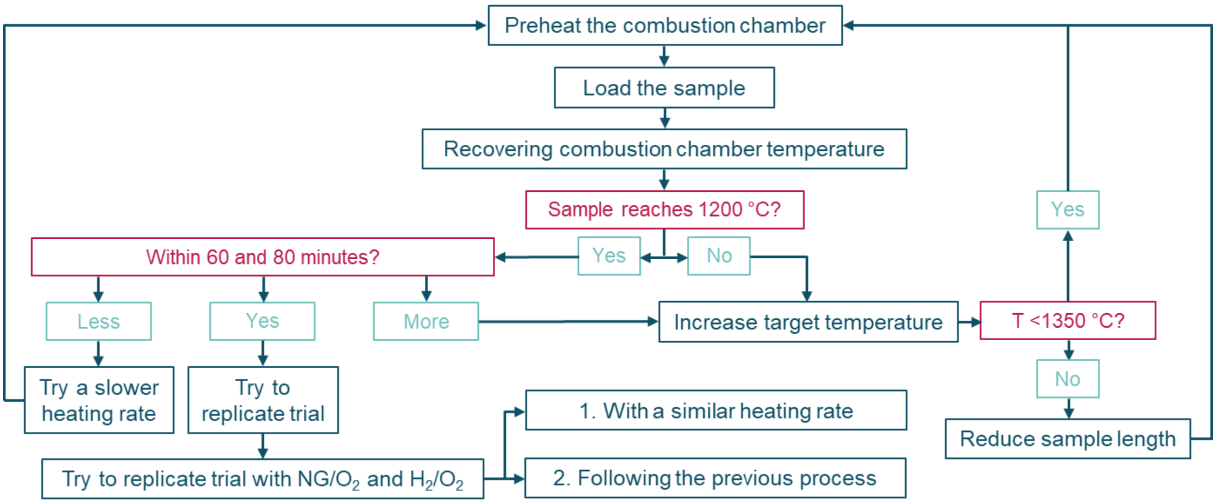


Figure 24. Schematic representation of the methodology followed to define the thermal cycle of the combustion chamber.

After several iterations, the final thermal cycles were defined as shown in Figure 12. In both combustion modes, the combustion chamber was preheated to 1250 °C prior to loading the sample. Upon opening the door, the chamber temperature dropped to approximately 900 °C due to heat losses.

- In the case of NG-air combustion, the selected operating mode was to set a holding temperature of 1250 °C, allowing the burner to operate at maximum power until the setpoint was recovered.
- For oxy-combustion, the temperature distribution was less homogeneous, which required the definition of a stepped heating rate up to 1260 °C, followed by a final holding stage at 1240 °C to stabilise the system.

As a result, in both air combustion and oxy-combustion conditions, the two thermocouples located at the centre of the sample successfully reached 1200 °C by the end of the 70-minute cycle. Moreover, the temperature difference between the maximum (T3) and minimum (T4) readings was kept to a minimum, indicating a high degree of thermal uniformity within the sample. The sample was unloaded after 70 minutes of treatment and allowed to cool in ambient air (Figure 26).

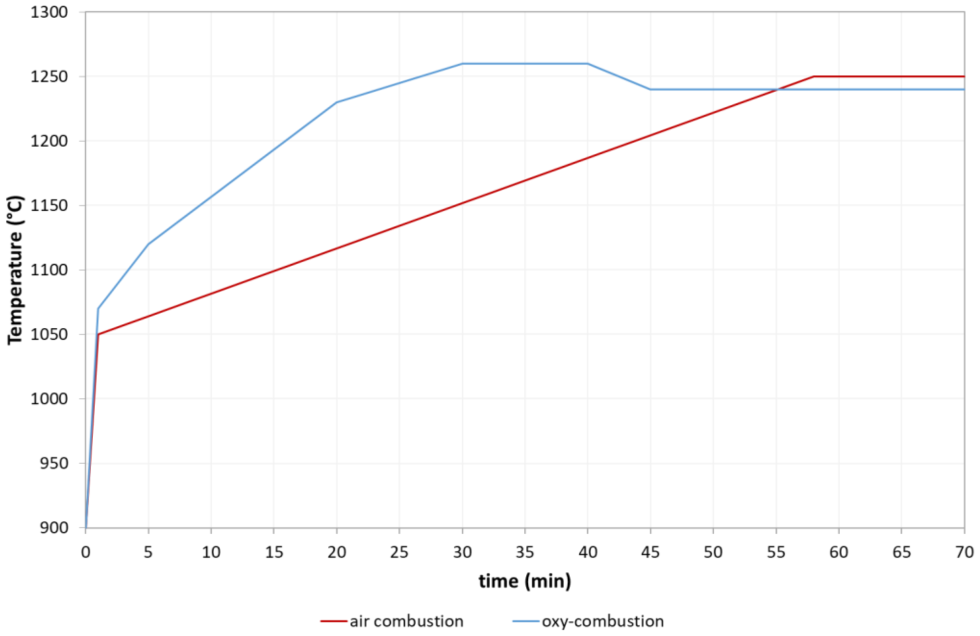


Figure 25. Thermal cycle set in the PLC for the trials.

Figure 26. Picture of the sample inside the combustion chamber prior to unloading it.

Results and discussion

Thermal cycles

As previously mentioned, each thermal treatment was performed twice per combustion atmosphere: once to measure weight loss, and once for the microstructural analysis of the oxides (as part of WP6). The corresponding thermal cycles for the samples and the combustion chamber under NG-air, NG-O_2, and H_2-O_2 combustion conditions are shown in Figure 27, Figure 28, and Figure 29, respectively.

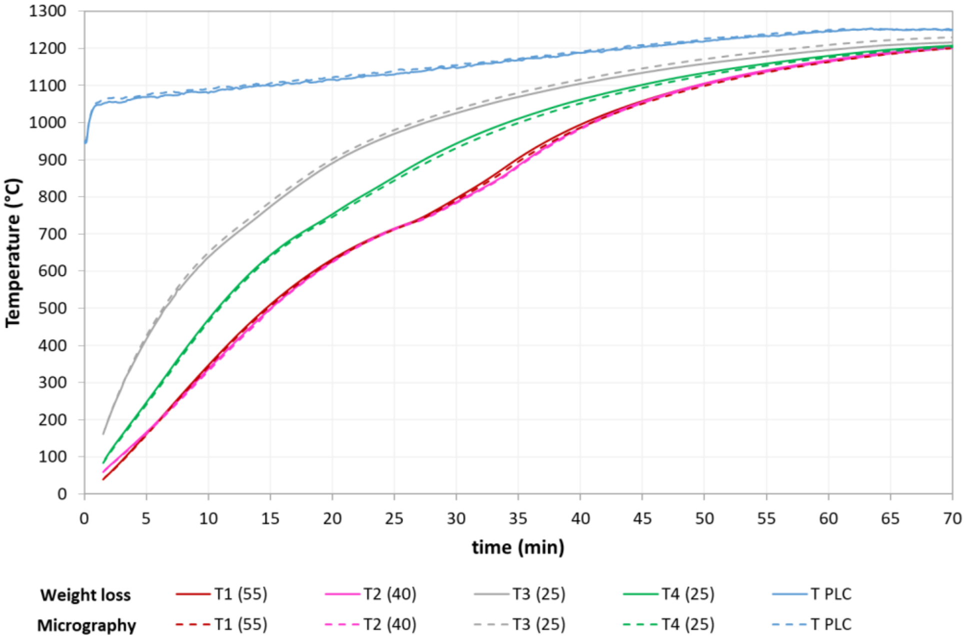


Figure 27. Thermal cycles of the combustion chamber and sample, NG-air tests. Continuous line represents the test for weight loss measurement and dotted line the test for microstructural analysis.

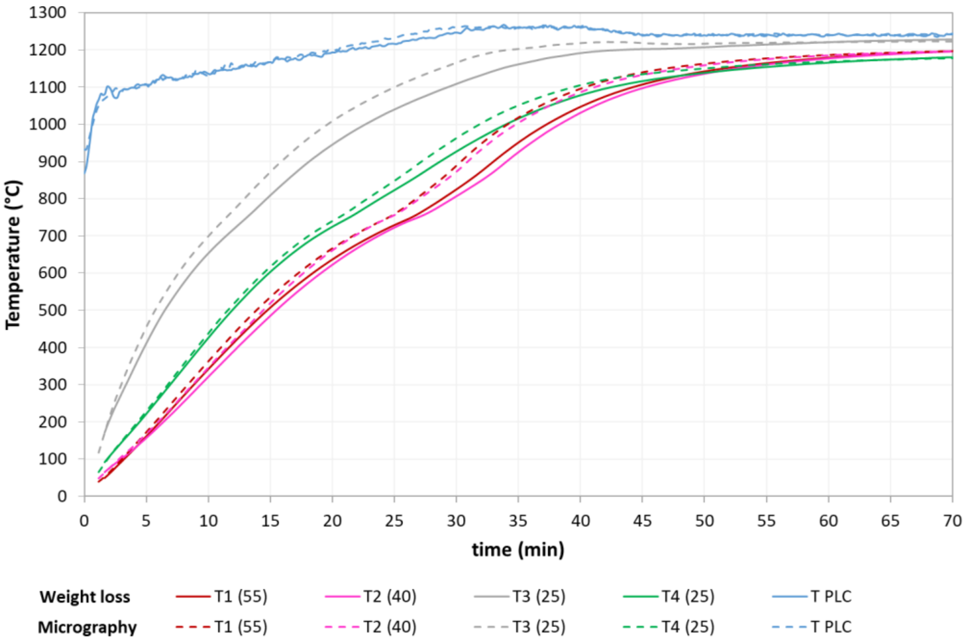


Figure 28. Thermal cycles of the combustion chamber and sample, NG-O_2 tests. Continuous line represents the test for weight loss measurement and dotted line the test for microstructural analysis.

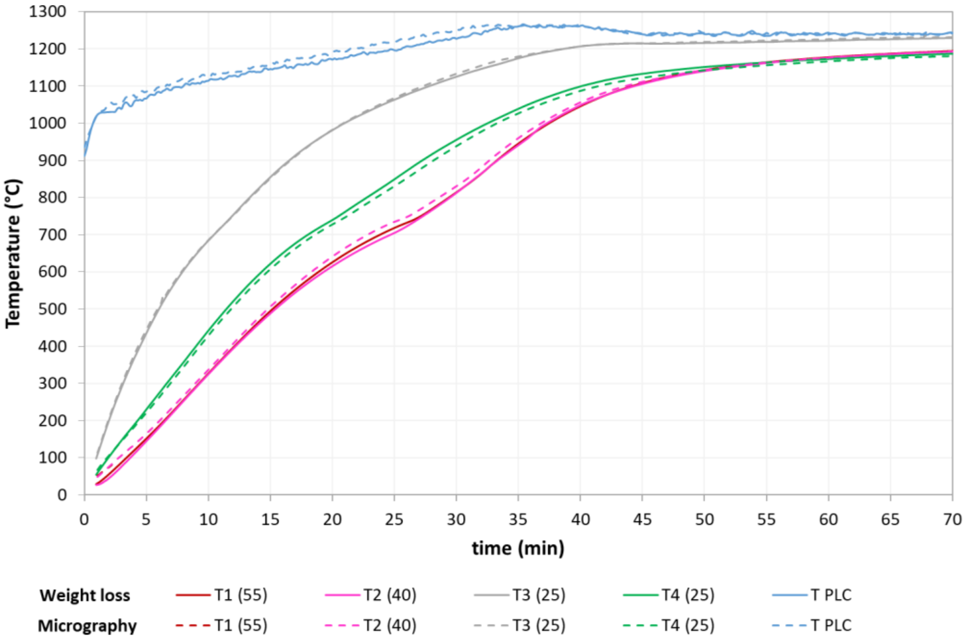


Figure 29. Thermal cycles of the combustion chamber and sample, H_2-O_2 tests. Continuous line represents the test for weight loss measurement and dotted line the test for microstructural analysis.

As observed, the tests demonstrated a high degree of repeatability, with minimal variation between repetitions in the NG-air and H_2-O_2 trials, and only a slight deviation in the NG-O_2 tests.

In terms of temperature homogeneity within the sample:

- NG-air combustion proved to be the most effective, achieving uniform temperatures across all monitored points by the end of the treatment. Only T3 (top, burner face, 25 mm depth) showed a slightly higher temperature.

- In the oxy-combustion trials, the temperature difference between T3 and the other thermocouples was more pronounced than in NG-air tests. However, all other thermocouples reached temperatures very close to 1200 °C, indicating an overall satisfactory thermal distribution.

Pressure, residual O_2, and fuel consumption

During the tests, pressure, flow rates, and residual O_2 levels were continuously monitored. Figure 30, Figure 31 and Figure 32 show the evolution of pressure and accumulated energy consumption (kWh) over time for the weight loss tests conducted under each combustion condition.

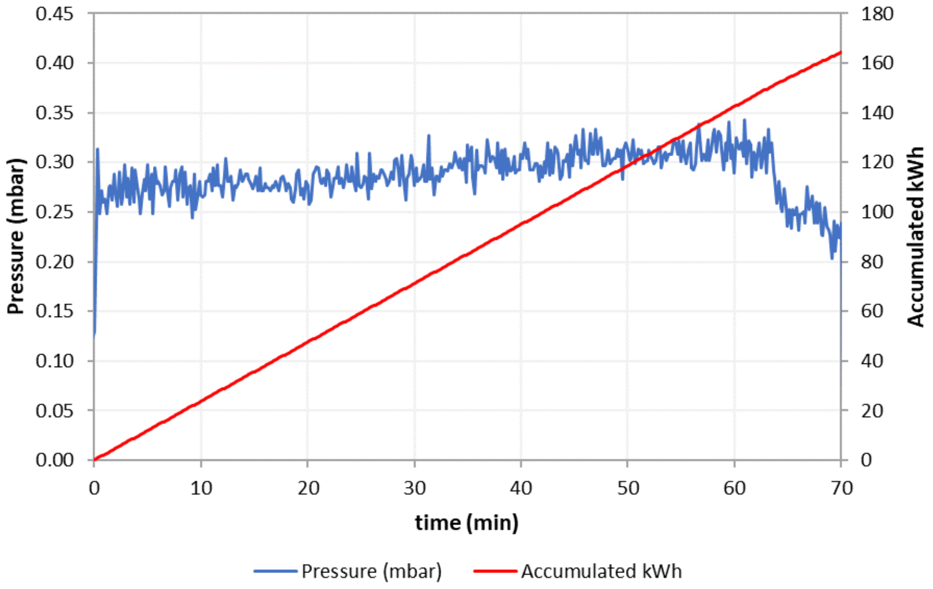


Figure 30. Evolution of pressure (mbar) and accumulated kWh during the NG-air test.

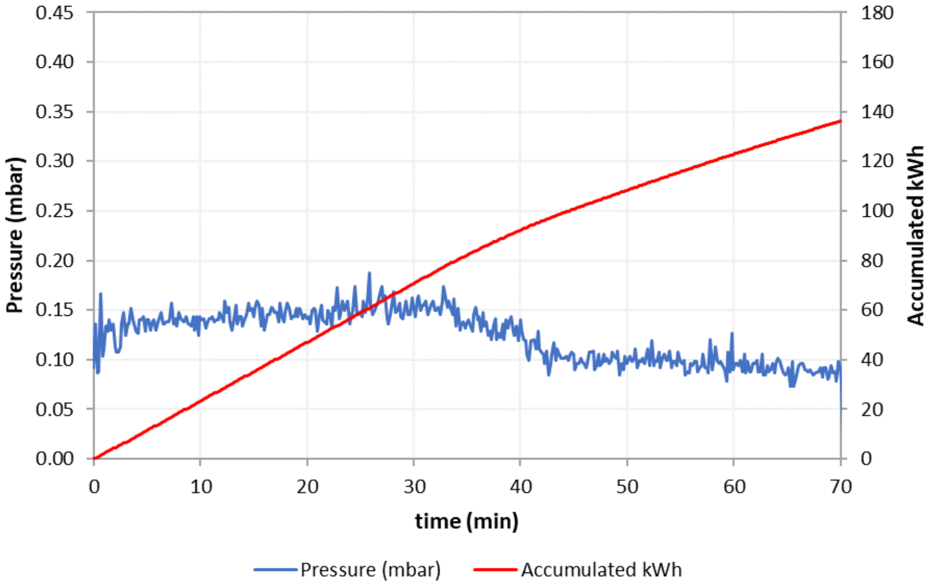


Figure 31. Evolution of pressure (mbar) and accumulated kWh during the NG-O_2 test.

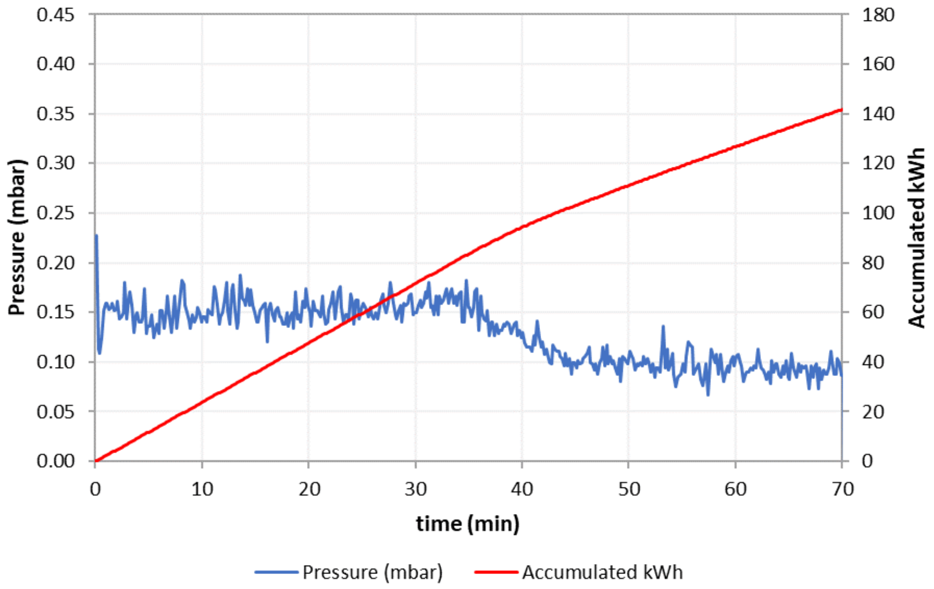


Figure 32. Evolution of pressure (mbar) and accumulated kWh during the H_2-O_2 test.

Since the combustion chamber was not hermetically sealed to the extraction system, pressure regulation was not possible, which explains the variations observed during the tests.

- In the NG-air case, during the first 62 minutes, and in the oxy-combustion cases, during the first 32–35 minutes, the burner operated at maximum power, resulting in a linear increase in accumulated kWh. The slight increase in pressure during these periods is likely attributable to the rise in temperature inside the chamber.
- The subsequent pressure decrease corresponds to the reduction in burner power and, consequently, in inlet flow rates, once the target temperature was reached.

Importantly, in all cases, negative pressure (depression) inside the combustion chamber was avoided, thereby preventing the ingress of ambient air and ensuring the integrity of the combustion atmosphere.

Figure 33, Figure 34, and Figure 35 present the evolution of residual O_2, fuel and oxidiser inlet flow rates, and accumulated energy consumption (kWh) during the weight loss tests for each combustion condition.

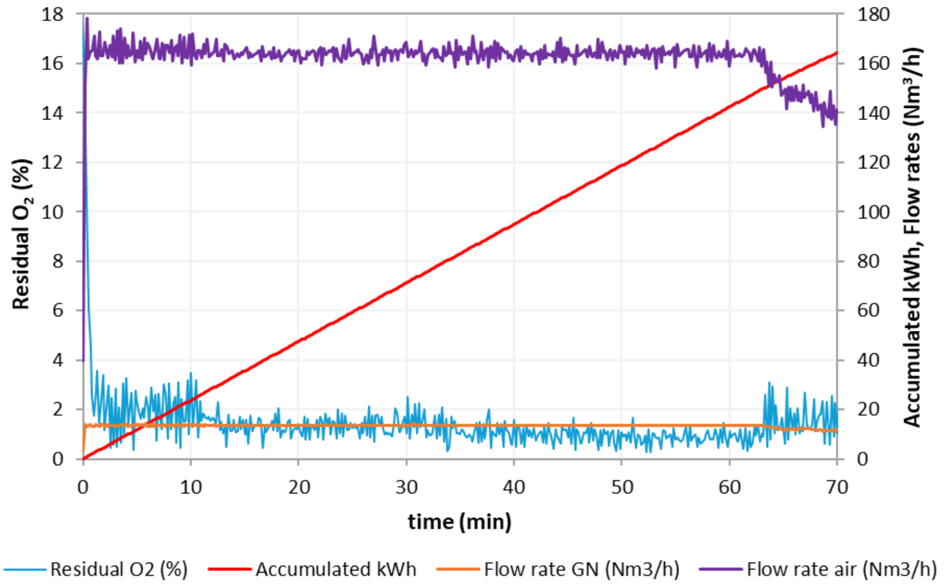


Figure 33. Evolution of the residual O_2 (%), inlet flow rates (Nm^3/h) and accumulated kWh during GN-air test.

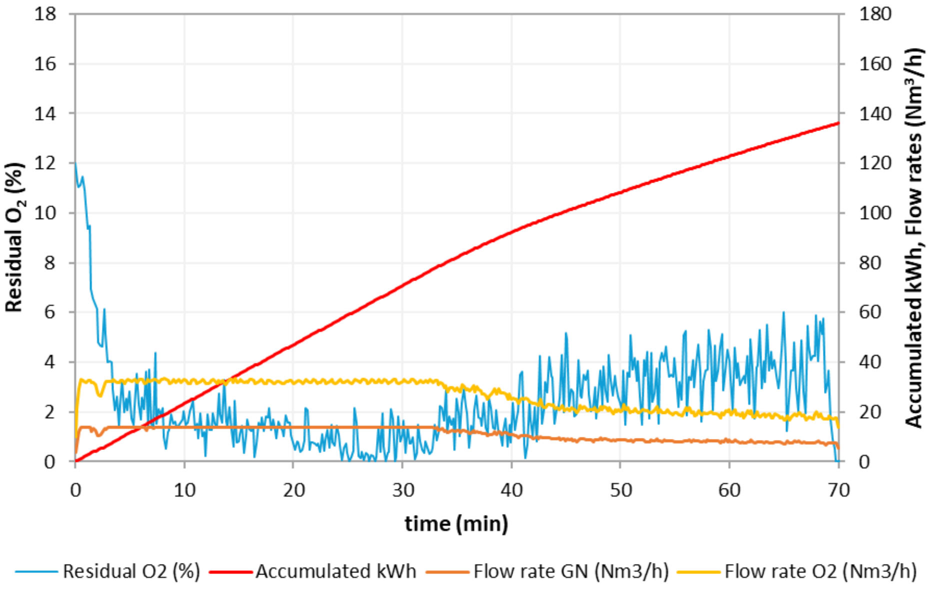


Figure 34. Evolution of the residual O_2 (%), inlet flow rates (Nm^3/h) and accumulated kWh during GN-O_2 test.

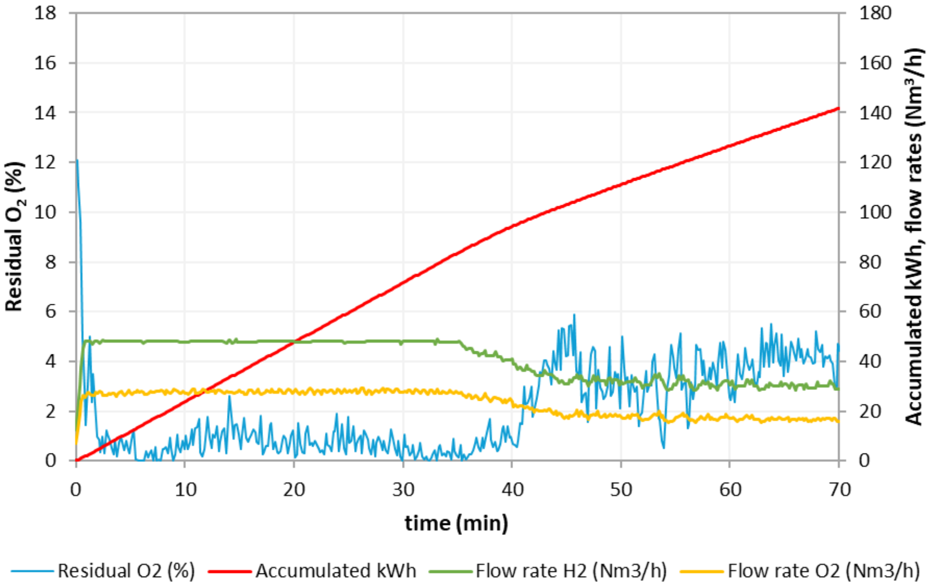


Figure 35. Evolution of the residual O_2 (%), inlet flow rates (Nm^3/h) and accumulated kWh during H_2-O_2 test.

As shown in the figures, the residual oxygen concentration dropped abruptly at the beginning of each test, immediately after the door was closed following sample loading. The O_2 concentration stabilised around 1% during the high-power phase.

As the burner power decreased, the residual oxygen levels began to rise, reaching approximately:

- 2% in the NG-air tests.
- 5% in the oxy-combustion tests.

The average residual oxygen values and the total fuel and energy consumptions for each test are summarised in Table 1.

As expected, the residual O_2 levels were higher in the oxy-combustion trials. However, these values remain within the typical range for this type of combustion and do not indicate any abnormal behaviour.

In terms of fuel and energy consumption, a significant reduction was observed when air was replaced by oxygen as the oxidiser:

- NG-O_2 combustion resulted in an average reduction of 19.47% compared to NG-air combustion.
- H_2-O_2 combustion achieved a 15.18% reduction in energy consumption relative to NG-air.

These results highlight the efficiency gains associated with oxy-combustion technologies, particularly in terms of energy use.

Table 1. Fuel and energy consumptions of each test.

Combustion	Test	Average residual O_2 (%)	Fuel consumption (Nm^3)	Energy consumption (kWh)	Savings over NG-air (%)
NG-air	Weight loss	1.47	15.79	165.14	-
	Micrography	1.45	15.71	164.32	-
	Average	**1.46**	**15.75**	**164.73**	-
NG-O_2	Weight loss	2.46	13.04	136.35	17.44
	Micrography	2.30	12.33	128.97	21.51
	Average	**2.38**	**12.68**	**132.66**	**19.47**
H_2-O_2	Weight loss	2.02	47.38	141.68	14.21
	Micrography	2.48	46.08	137.77	16.16
	Average	**2.25**	**46.73**	**139.72**	**15.18**

Weight loss

To determine weight loss, the samples were weighed before the tests and again after shot blasting to remove surface oxides. The shot blasting process was performed using GL 025 angular steel shot to ensure thorough cleaning of the oxide layer.

Additionally, weights were recorded immediately after the tests, prior to blasting, to estimate the weight gain due to oxidation. However, it is important to note that these intermediate measurements are not entirely reliable, as some oxide scale was lost during sample handling and transfer, potentially affecting the accuracy of the oxidation gain estimation.

The final calculated weight losses were:

- 0.97% for NG-air combustion.
- 1.26% for NG-O_2 combustion.
- 1.58% for H_2-O_2 combustion.

The weight loss observed for NG-air combustion aligns well with the expected value of approximately 1%, confirming the validity of the methodology.

The incremental increases in weight loss were:

- +0.29% from NG-air to NG-O_2
- +0.32% from NG-O_2 to H_2-O_2

This corresponds to a 29.90% increase in weight loss for NG-O_2 and a 62.89% increase for H_2-O_2 relative to NG-air combustion. All data are summarised in Table 2.

In any case, it is worth mentioning that the AMOB's structural steel is 12 m long, increasing the surface-to-volume ratio by 15% compared to the samples used in this study. Therefore, it can be expected that the weight loss in the industrial samples will be somewhat lower.

Table 2. Mass measured before heat treatment, after heat treatment and after blasting.

Combustion	$m_{initial}$ (kg)	m_{test} (kg)	m_{final} (kg)	weight loss (%)
NG-air	138.95	139.10	137.60	0.97 ± 0.07
NG-O_2	138.40	138.75	136.65	1.26 ± 0.07
H_2-O_2	139.45	139.80	137.25	1.58 ± 0.07

Figure 36 shows photographs of the samples taken at three stages: before the tests, after the tests, and after shot blasting.

At first glance, it appears that the oxide scale formed during H_2-O_2 combustion was more easily detached compared to that formed in the NG combustion samples. This observation suggests a potential difference in oxide adhesion or morphology between atmospheres. However, a dedicated microstructural study will be required to confirm this hypothesis, which will be addressed in the scope of WP6.

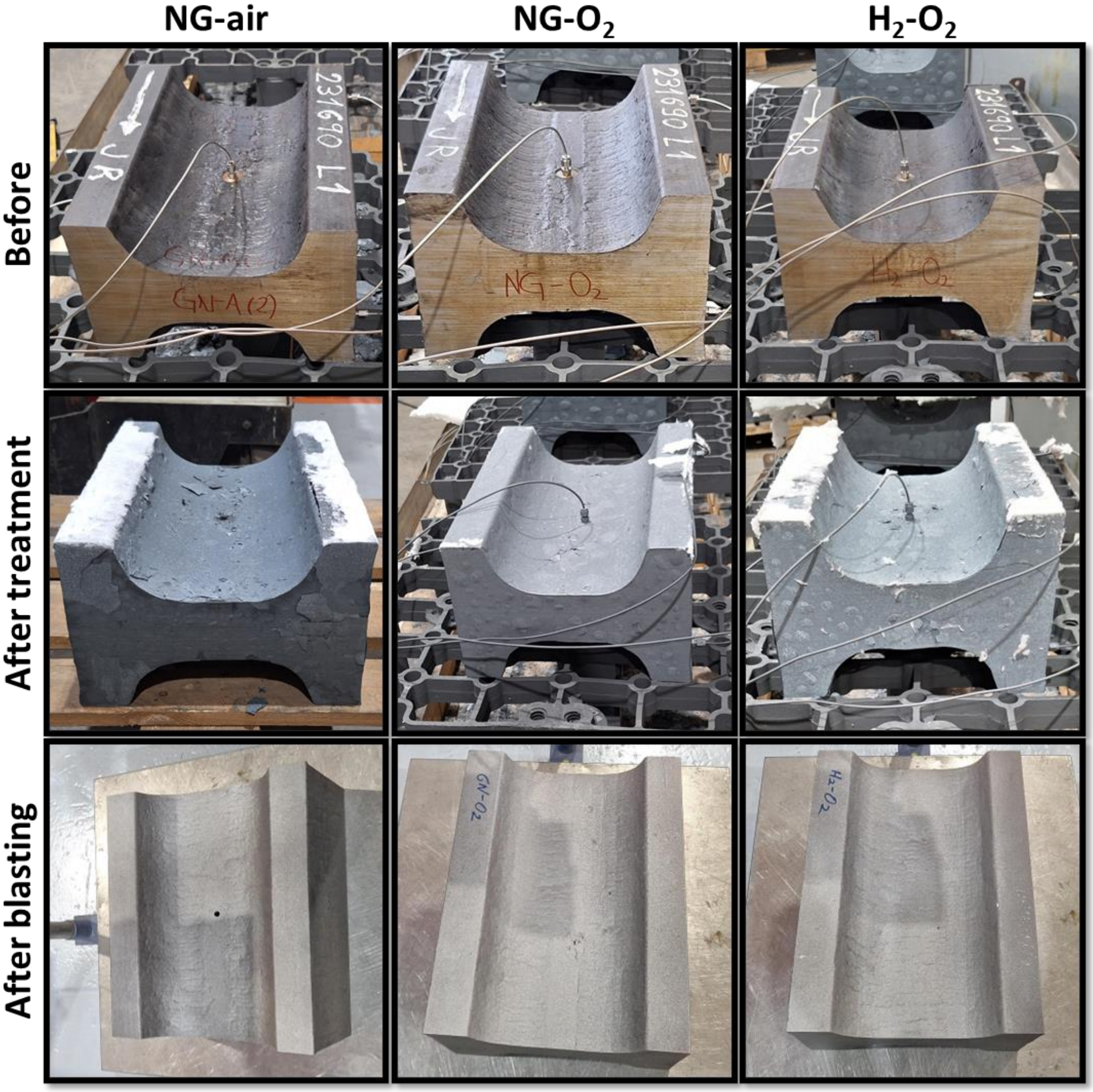


Figure 36. Pictures of the samples before heat treatment, after heat treatment and after blasting.

Conclusions

- The industrial heat treatment of the Olaberria reheating furnace was successfully simulated, achieving 1200 °C throughout the entire sample within the 70-minute treatment period, with minimal temperature heterogeneity across the monitored points.
- The tests were conducted in duplicate, demonstrating a high degree of repeatability, both within each combustion condition and between different combustion atmospheres.
- The use of oxy-combustion led to significant fuel savings: an average reduction of 19.47% for NG and 15.18% for H_2 compared to NG-air combustion.
- Replacing air with oxygen as the oxidiser resulted in increased weight loss, with values 29.90% higher for NG-O_2 and 62.89% higher for H_2-O_2 compared to NG-air combustion.
- Visually, the oxide scale formed during H_2-O_2 combustion appeared to detach more easily than that formed in NG combustions. However, further investigation is required to confirm this observation.

Indirect heating applications of hydrogen fired burners

Introduction

As commented in the previous section for reheating furnaces, continuous galvanizing and annealing furnace full decarbonisation can be achieved by means of using green hydrogen as fuel. Blends of H2/NG higher than 75% of H2 (volume) will reduce the carbon footprint above 50%.

Current standard technologies used in CGL/CAL for the radiant tubes sections include:

1. Recuperative burners
2. Self recuperative burners
3. Regenerative burners

For recuperative burners, radiant tube shapes that are frequently installed in this kind of furnaces are U and W. In these cases, the burner is placed in one of the entrances of the radiant tube and in the opposite exit a plug-in heat recuperator is installed. Regulation for this units is mainly proportional, being able to operate in a turn down of 1:4.

For the two remaining technologies, the shapes of the radiant tubes associated are straight (I), P or double P shapes. In these cases, there is only one exit, and the product of combustion are sucked out of the tube taking advantage of the design of the burner through a flues/air heat exchanger designed to maximize the heat exchange at nominal power Normally, the combustion control is digital (On/Off) without the capability of output power modulation.

Here below a picture of the two more relevant radiant tubes shape is shown in Figure 37. Typical radiant tube shapes: double P (left) and W (right).

Figure 37. Typical radiant tube shapes: double P (left) and W (right).

Design and engineering of indirect heating burners

To design a new system in the indirect heating several requirements should be considered. Special care should be address to the radiant tube material, to limit the impact of the new composition of the products of combustion and some unburnt hydrogen. Next figure shows the difference in volume of the flue gas composition between standard natural gas firing versus pure hydrogen for a 2 % vol of oxygen excess combustion Thus, good regulation for the combustion should be assure.

Table 3. Comparison of combustion atmospheres.

vol.%	Natural gas Combustion	Hydrorgen Combustion
O_2	2	2
N_2	72.3	66.6
CO_2	8.8	0
H_2O	16.9	31.4

However, the combustion of hydrogen is feasible in these type of furnaces, specific modifications on the burner should be carried out to keep normative requirements in terms of the emission to air (fulfilling new BREF normative for emissions to air). This increase in the potential NO_X emission is linked to the raise of the adiabatic temperature of the flame when compared to the natural gas combustion. This is a common issue in both direct and indirect heating processes.

State of the art commercial burners with low NOx operation working modes are going to be be analysed and tested to create a robust and complete characterization of the possibilities in the indirect heating process. Different approaches can be found in the market to reduce the NOx emissions with minor disadvantages in the radiant tubes.

Safety considerations for indirect heating

Besides all the comments in terms of safety use of hydrogen mentioned in the previous section (*Safety considerations*), to align the use of hydrogen as fuel for indirect heating to the current normative, some specific points should be evaluated.

To comply with the UNE-EN ISO 13577, safety interlocks, dedicated shutoff valves and burner control units with flame monitoring must be considered. Since the hydrogen flame doesn't create a good ionization response, UV detector is the proper alternative to evaluate flame quality below the autoignition temperature (above that temperature, the system can be avoided with no further complication.

In terms of gas train safety requirements, burner control units are connected to shutoff valves that interrupt the gas flow to the burner when there are some issues during the combustion. Hence, tightness control of the gas train is also mandatory to isolate the gas form the burners whenever the situation requires it.

To sum up the main interlocks that should be considered

1. Low air pressure.
2. Discrepancy in target air/gas ratio.
3. Low/high gas pressure.
4. Cooling system ok.
5. Nitrogen supply pressure ok.
6. LEL detectors ok.

Experimental campaign set up

The future DOE for the indirect heating using hydrogen as fuel should include dedicated tests to evaluate different approaches that the suppliers use to generate robust, high efficiency and low emissions burners.

To carry out the trials the pilot scale laboratory that AMI has inside the Asturian production site will be used. This facility is directly connected to the industrial gas grid, giving the opportunity to feed the pilot lab with a 24/7 gas feeding. Since there is no current hydrogen availability in the site, a new hydrogen supply system has been acquired (see section *Hydrogen supply* above).

The pilot scale lab already running includes a fully instrumented and partially automatic duplicate of an industrial CGL/CAL with the possibility of firing up to two radiant tubes (being the design max power 400 kW). The combustion chamber simulates the strip that passes through the industrial furnace with a water heat exchanger. Thus, the energy deployment to the strip can be evaluated and monitored along the time and the trials.

Here below a photograph of the camber is included in Figure 38.

Figure 38. AMI pilot scale combustion chamber at Gijon site.

To determine the efficiency of the units tested and the overall performance of the whole system, dedicated thermocouples and other sensors are installed in the chamber and in the radiant tube itself. To complete the characterization when testing, flue gas analysers are also in service.

All the process parameters and signals from the trials are sent to a specific system to compile and record them, for further analysis.

Since the project running includes the use of pure hydrogen as fuel, some adaptations and new erections must be done before running the trials packages. Thus, the main changes are detailed here below.

First, new automatic pressure regulating valves are installed downstream the new hydrogen feeding for reducing the gas pressure to working pressure defined in a range of about 150 mbar, similar to the application of natural gas.

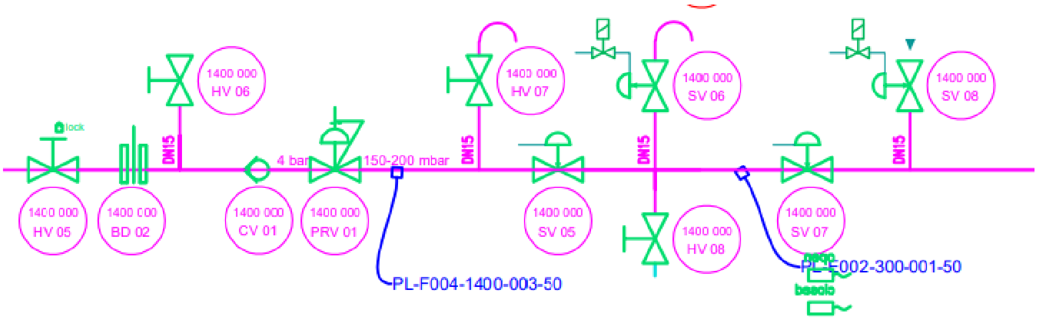


Figure 39 Hydrogen double shutoff valve and intermediate purge P&ID

On one hand, high pressure piping of the supply system was manufactured in AISI 316S stainless steel to avoid diffusion and embrittlement of the system at high pressure. On the other hand, for low pressure application (lower than 8 bar), standard carbon steel was installed since the previous issues described disappear.

To diminish the apparition of explosive atmospheres during long stoppages when the hydrogen train is not blinded, double valve with an intermediate open vent was installed outdoors. Therefore, in case of leakage of any of both valves, the gas is relief outside of the building.

The hydrogen is regulated and measured in the laboratory mixing station. Any blend between natural gas and hydrogen can be set up easily by measuring both fuel gas accurately by means of orifice plates and differential pressure transmitters. After the mixing station a tightness control is installed to comply with the normative of combustion UNE EN ISO 13577.

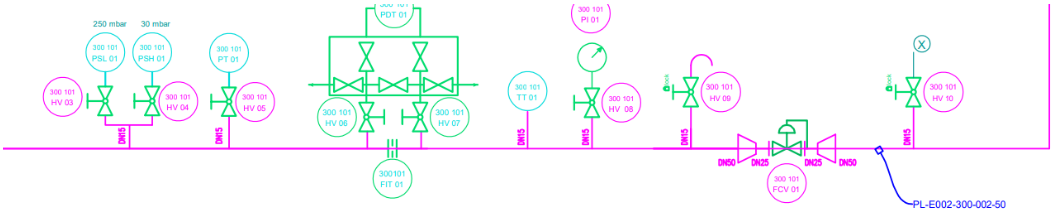


Figure 40 H2 gas train mixing station P&ID

Downstream, a flow control valve is installed for each one of the branches that feed each burner to control and adjust the desired fuel gas to be supplied to the burner.

Air train is composed by a combustion fan controlled by a variable speed driver. This allows to have more stable and accurate flow control. The air was measured by a dedicated orifice plate and a differential pressure transmitter.

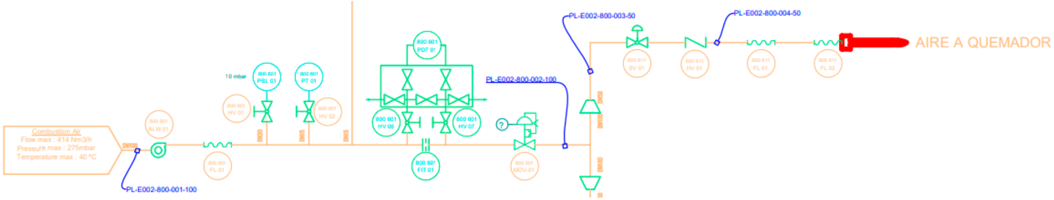


Figure 41 Air train to burner P&ID

Connections to the burner were made with flexible metallic hoses without any detectable leakage of fuel.

The flue gas pressure is also regulable by an exhauster equipped with a variable speed driver. The pressure transmitter is installed just at the burner flue gas outlet. Furthermore, emissions are continuously monitored by Siemens Ultramat 23 (O_2, NO, SO_2 & CO) analyzers.

The atmosphere of the chamber is monitored using different instruments, such as pressure transmitter to keep a nitrogen millibaric overpressure, dew point sensor to keep negative dew point values and oxygen sensor with ppm resolution. Thus, the outer atmosphere of the radiant tubes partially replicates the current industrial CGL/CAL furnaces.

The heat exchanger that simulates the strip in between the two radiant tubes that are allocated in the combustion chamber creates a temperature jump once the water flows through the chamber, being measured by thermocouples installed at inlet/outlet of the heat exchanger. Besides, the flow rate of cooling water is being measured and cool down by an aero cooling unit outside of the laboratory building.

To enlarge the safety inside the laboratory lower explosive level detectors were installed and adjusted in several locations of the laboratory building for hydrogen gas leak detection. These sensors are connected to a common cabinet that records and set the alarms in case of leakage detection, stopping furnace operation in case of high leakage warning.

Conclusions and next steps

Main conclusions are summarized here below:

- Dedicated revamping in the pilot plant to be able to use new burner units with hydrogen as fuel was studied and complete during the task.
- As a result, a new gas and air train has been designed to cope with new requirements in terms of safety (new sensors for H_2 train) and process (new air fan acquisition due to air pressure needs for the burners to be tested)
- To comply with combustion normative (UNE-EN ISO 13577) and enlarge the safety operation, special attention has been addressed to determine the interlocks that should be added to the pilot plant program.
- Since there are two different technologies and radiant tube shapes that are going to be tested, some minor changes have been pointed out to use them with no larger furnace revamp
- As a result, all the needs and modifications have been listed and executed in the pilot plant to be able to start with the tests.

Conclusions and next steps

All objectives defined in the Amendment Nr. 2 has been fully accomplished.

First, dedicated revamping in the AMI semi-industrial pilot plants for direct and indirect heating operations was studied and completed, in order to be able to use new burner units with hydrogen as fuel and NG/H_2 blends. The burner integration has been designed to cope with new requirements in terms of safety and process. Special attention has been paid to determine the interlocks. As a result, all the needs and modifications have been listed and executed in the pilot plant to be able to start with the tests.

Furthermore, the successful operation of AMS self-recuperative burners with H_2 had been validated in preliminary pilot plant tests. Based on these results, the design of the retrofitting of the AMS tunnel furnace combustion system has been accomplished.

Finally, the industrial heat treatment of the AMOB reheating furnace was successfully simulated with a high degree of repeatability, for NG/H_2 oxy-combustion versus the baseline NG/air combustion, leading to significant fuel savings, but increased weight loss. Optimization of heating curves may allow to cope with this issue, as it will be assessed in the industrial campaign.

As next step, a long-term demonstration campaign is executed in WP6, for both AMI direct and indirect heating furnaces, to evaluate the retrofitting of furnaces for hydrogen operation, based on the testing methodology and design defined in this task. Also, in WP6, the tests in industrial demonstrations will be performed, based on the results of the preliminary tested reported in this document.

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