

D5.3 Report on results of the aluminium use case implementations

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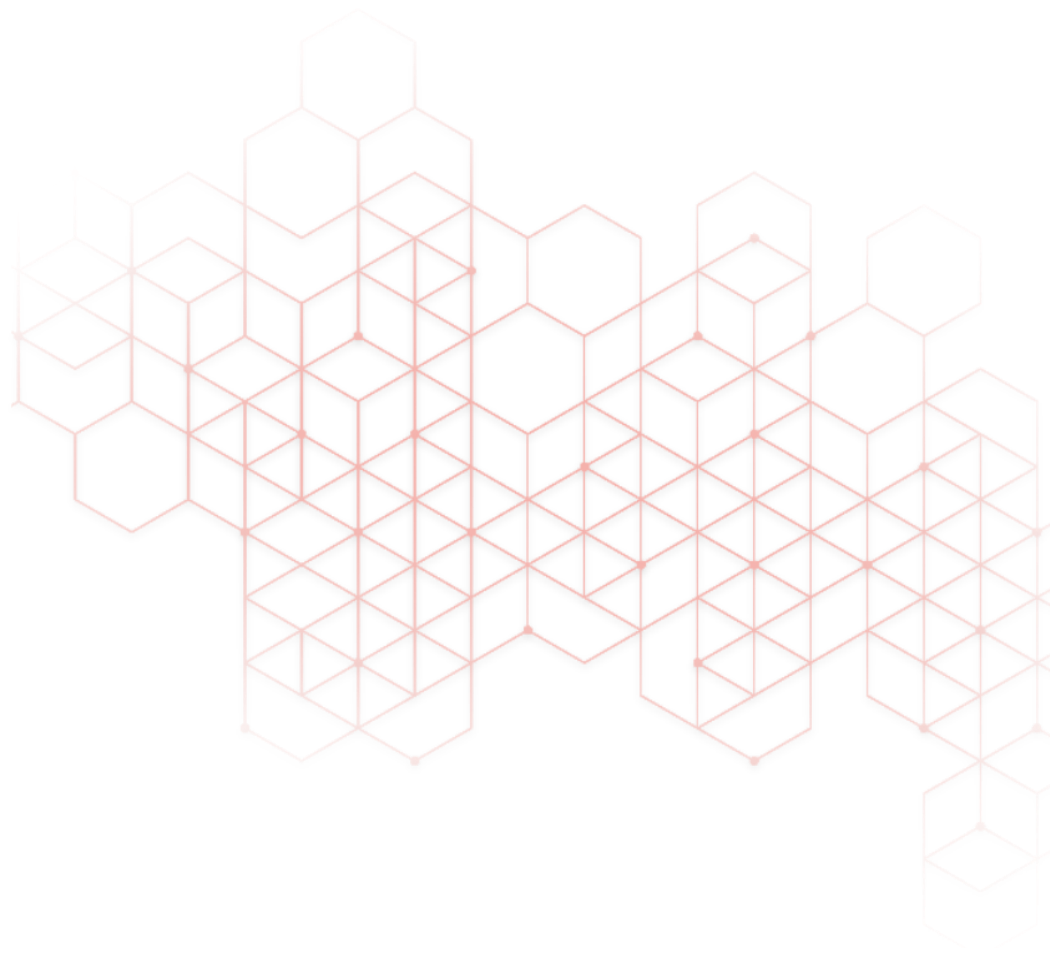
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October 2026



Credits

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This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101091456.

Technical references

Grant Agreement N°	101091456	Acronym	HyInHeat
Full Title	Hydrogen technologies for decarbonization of industrial heating processes		
Work Package (WP)	WP5 – Demonstration of H2 heating solutions in aluminium production processes		
Authors	Angel Sanz (GHI), Anastasios Psarros (Metlen), Jessica Montero (Befesa), Louis Piquard (C-TEC), Emilien Clement (C-TEC), Pierre-Yves Menet (C-TEC), Iban Vicario (Tecnalia), Magdalena Nowak-Coventry (TME), Eduardo J. Pérez (BSC), Carlos Guillamón (BSC), Daniel Mira (BSC), Johannes Losacker (IOB), Alex M. Garcia (IOB), Nico Schmitz (IOB), Christian Wuppermann (IOB), Andreas Buchholz (Speira), Esin Iplik (Linde), Tobias Tillmann (RWT-GHI)		
Leading organisation	C-TEC		
Date of publication	23/10/2026		
Contributors			
Document Type	R – Document, report		
Document Title	Report on results of the aluminium use case implementations		
Dissemination Level	PU - Public		

Document history

Version	Date	Partner	Author
1	23/10/2026	GHI	Angel Sanz

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List of abbreviations

Abbreviations	Explanation
Am ³ /h	Aparent cubic meters per hour
AMI	ArcelorMittal Innovation
AMOB	ArcelorMittal Olaberria-Bergara
AMS	ArcelorMittal Sestao SL
ATEX	Explosive atmosphere
BEF	Befesa Aluminio SLU
BSC	Barcelona Supercomputing Center
CA	Calcium aluminate
CAPEX	Capital expenditure
CCS	Cold crushing strenght
CEL	Celsa Armeringsstål AS
CFD	Computational Fluid Dynamics
CTEC	Constellium Technology Center
CO ₂	Carbon dioxide
DI	Density index
DOM	Discrete ordinate method
EAF	Electric arc furnace
EDC	Eddy dissipation concept model
H ₂	Hydrogen
H&S	Health and Safety
IR	Infrared sensor

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KPI	Key Performance Indicator
LES	Large Eddy Simulations
LTOF	Low temperature oxy fuel
m ³ /h	Cubic meters per hour
MILD	Moderate or intense low-oxygen dilution
MYT	Mytilinaios Anonimi Etaireia (Metlen)
NG	Natural gas
Nm ³ /h	Normal cubic meters per hour
NTNU	Norwegian University of Science and Technology
NO _x	Nitrogen oxides
OPEX	Operating expenses
O ₂	Oxygen
PaSR	Partially Stirred Reactor
P4P	Processes4Planet
PoDFA	Porous Disc Filtration Apparatus
P&ID	Process & instrumentation diagram
RDI	Research Development and Innovation
RUL	Refractoriness under load
RANS	Reynolds averaged Navier-Stokes
RWTH-GHI	Rheinisch-Westfaelische Technische Hochschule - Institut für Gesteinshüttenkunde Aachen University - Institute of Mineral Engineering
SEC	Specific Energy Consumption
SMRH	Surface Melt Rate per Hour
SRIA	Strategic Research and Innovation Agenda
SPE	Speira GmbH

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SPIRE	Sustainable Process Industry through Resource and Energy Efficiency
SWE	Swerim AB
TA	Computer assisted thermal analysis
TME	Toyota Motor Europe NV
TMC	Thermal-Mechanical-Chemical
WP	Work package
WSGGM	weighted sum of gray gases model

1 Introduction

The present deliverable reports the results obtained within Work Package 5 (WP5) of the HyInHeat project, which aims at demonstrating the feasibility of hydrogen use in high-temperature industrial processes. In the aluminum sector, the objective of WP5 is to evaluate the integration of hydrogen into industrial remelting furnaces and to assess its impact on process performance, product quality, and environmental emissions.

The following document shows the results of the tests done by the different Aluminium demonstrators of the HyInHeat project. Each of the demonstrators has been undertaking several tests with hydrogen and compared them against the existing baseline with natural gas.

- Liquid metal transfer
- Rotary recycling furnace
- Reverberatory melting furnace
- Reverberatory holding furnace and pusher furnace studies
- Annealing furnace with H₂/O₂ combustion
- Lab scale melting furnace

2 Preheating station for liquid metal transfer

2.1 Introduction

The following demonstrator is the preheating station for ladles that transport aluminium within the Metlen factory in Greece. The retrofit for this demonstrator consists on the replacement of the existing cold air burner with an oxyfuel burner capable of firing both with natural gas and hydrogen as fuels.

The following targets are set for these tests:

- Test the use of H_2+O_2 in the ladle heating station.
- Metal quality: Equipment testing and trials with metal as received from the plant, $NG+O_2$, $NG+O_2$ after 12h and H_2+O_2 heating of the ladles.
- Check safety procedures.

2.2 Tests with oxyfuel burner for preheating ladles

Installation of the hydrogen and oxygen gas supply panels is performed by Linde Greece followed by the installation of the leak detectors. Bundle locations are separated by each other and protected from the production environment as shown in the photo below.



Figure 1: Safety walls for hydrogen and oxygen bundles

After the supply system, pipelines are installed to connect the bundles to the burner flow skid. Both pipelines are purged with inert gas and leak tested.

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Figure 2: Bundles delivered after safety procedures

A gas safety seminar is given to the operators of the ladle preheating station about both hydrogen and oxygen. The flow skid is connected to the pipeline and the burner is installed on the hydraulic arm. The media flow is established via flexible hoses to the burner. Another leak check is performed with an inert gas for the skid and hose connections. An initial test flame is used to confirm the flame shape and behavior without a ladle at the preheating position.



Figure 3: Flow skid mounted on the wall and the control cabinet on the hydraulic cover



Figure 4: Test flame without ladle for confirmation

2.2.1 First test with hydrogen

The first ladle to be tested is delivered with 4.2 tons of molten aluminum. Firing onto molten aluminum with full power of 135 kW results in visible flame through the tapping hole, which is also the situation with the original Air-NG burner. When the flame has less space to develop, combustion completion reaches the tapping spout. After the observation, pilot mode is established to keep temperature which prevents the flame formation outside of the ladle. After 3 h of pilot mode, the wall temperature is measured at 680 C.

The hydrogen consumption for the test was 3,1 kg.

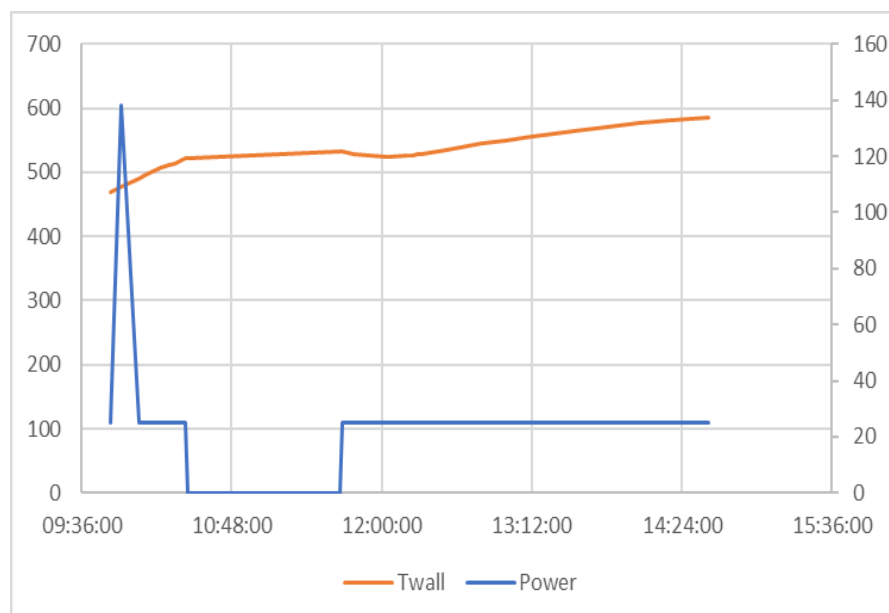


Figure 5: First test with hydrogen

2.2.2 Second test with hydrogen

The next ladle to be tested is delivered empty and at around usual return temperature to assess the full preheating cycle. It reached the target temperature in about 4.5 h with an average of 81 kW power. This operation is performed at 160 kW with the Air-NG burner, and the investigations of the savings are explained in deliverable 7.1.

The consumption of hydrogen is 12 kg in this test, the result is a better performance when compared to natural gas, the optimum temperature is reached in 4h instead of the typical 6h when using natural gas.

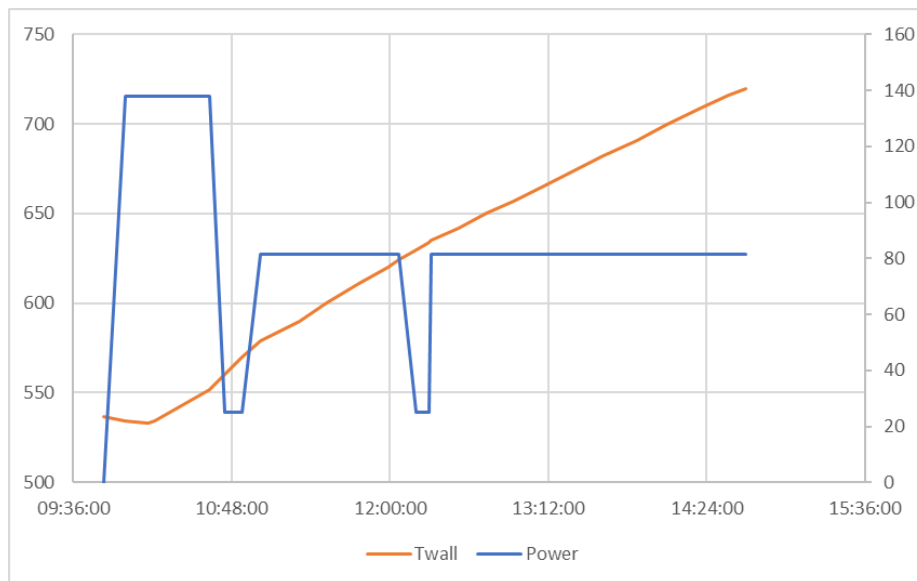


Figure 6: Second test with hydrogen

2.2.3 Third test with hydrogen

Another test is performed on a ladle that has 800 kg of frozen aluminum at the bottom. Melting process is performed with average of 62 kW power in 4 h.

Hydrogen consumption at the end of the test was 8 kg.

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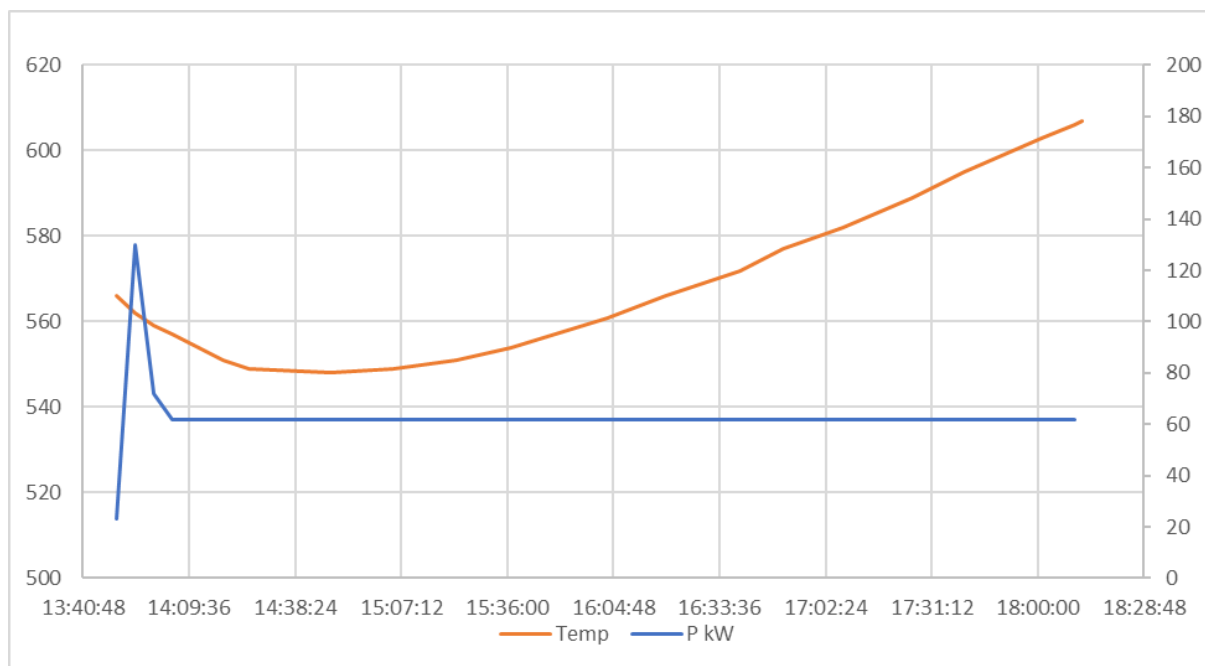


Figure 7: Third test with hydrogen

2.2.4 Fourth test with hydrogen

A final test is performed with a half full ladle with 2 tons of molten aluminum for temperature keeping at an average power of 58 kW. After 6 h of operation the trial is shut down and the molten aluminum is sent to the holding furnace. No additional dross is observed given the half full ladle has enough space for the flame development. Afterwards the equipment is dismantled and packed by Linde marking the successful hydrogen oxyfuel operation at the ladle preheating station.

Hydrogen consumption in the test is 11,8 kg.

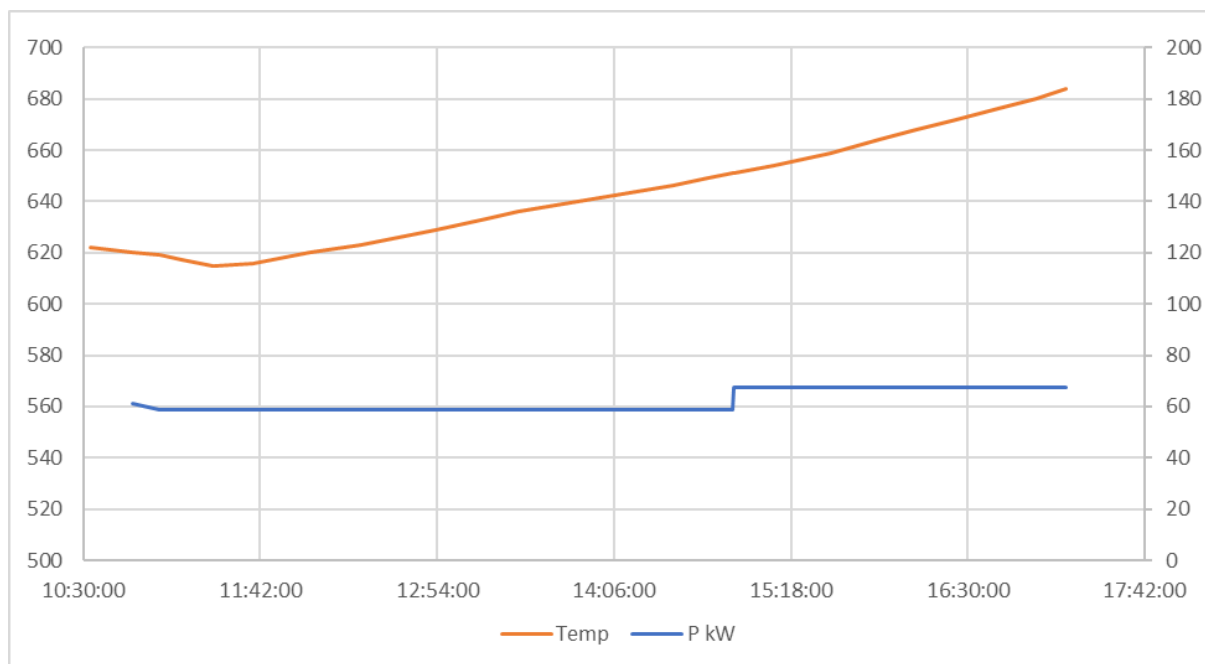


Figure 8: Fourth test with hydrogen



Figure 9: Linde and Metlen team after the succesful trial

2.3 Aluminium quality tests

The installation of Metlen for the heating of the crucibles was modified to admit the preheating of the ladle with H₂ and O₂. Different trials were performed to adjust the system.



Figure 10: Test with H₂+O₂ in crucible #3.

In the case of the study of the effect of the H₂+O₂ combustion and compare it with the Natural Gas (NG) + O₂, different tests were performed.

2.3.1 Baseline NG + O₂ trials

Trial starts pouring at 860°C at a preheated ladle at 480° C 4,500 kg of aluminium. Samples were obtained to compare the quality as received.

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The ladle was placed in the heating position and remained without heating till it reaches 750°C. After 30 minutes heating at 750°C with NG+O₂, samples were obtained.

After 12 hours of holding the molten metal in the ladle with the NG+O₂ burner, samples are obtained. This trial was performed to simulate the operations where the metal must be maintained in the ladle before sending it to the process plant. The melt temperature was held at 800°C-820°C.

2.3.2 Analysis of H₂ + O₂ trials

The ladle is put in the ladle preheating installation with 4,240 kg of molten aluminium and it started the maintenance heating of the ladle with H₂. Tests finished after 2 hours of maintain the metal heated with the H₂+O₂ burner and samples were obtained.

2.3.3 Aluminium quality determination:

To determine the quality of the obtained aluminium in function of the employed combustion atmosphere, different equipment has been employed.

To characterise the quality of the aluminium, different control systems were used: the K-Type mould, the dross test (including calculation of the sample density), and the thermal analysis.

For the determination of the density index (DI) and the dross test index, a Martech VTCM0017 vacuum equipment was employed, which includes a hydrostatic balance. The following figure shows an example of the equipment.



Figure 11: Vacuum equipment and scale model Martech VTCM0017.

Another way to determine the aluminium quality is employing the K-Type test, which determines the quality in function of the total inclusions or oxides determined in the observation areas and the total number of analyzed areas and it also gives an idea of the fluidity of the alloy.

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Figure 12: K-mold test equipment and obtained samples.

The computer-assisted thermal analysis (TA) studies the solidification path of an aluminium molten sample, determining the main solidification characteristics and also the presence of porosity.



Figure 13: TA test equipment and obtained samples.

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Quality samples were obtained from:

- K-Type.
- Vacuum test,
- Dross test.
- Thermal analysis steel cup.
- Thermal analysis sand cup.

In the next figure we can observe the obtained samples of one of the trials.



Figure 14: Test samples obtained in the H₂+O₂ trial.

2.3.3.1 Vacuum and dross test:

We analyzed the specimens obtained in the dross-test equipment. In the next picture, we can compare the shape and internal surface of obtained samples.



Figure 15: Example of test samples obtained in the vacuum and dross test: a) Air; b) Vacuum; c) Dross.

It can be observed, as is logical, that the greatest expansion of the specimen occurs in the "dross" sample, which has been solidified at 5 mbar. We see below the density values obtained in relation to the measurement in air and in water of the samples obtained in the atmosphere, under vacuum conditions (80 mbar) and dross test (5 mbar).

The DI value corresponds to the Density Index (DI), which is used to define the quality of the material according to the oxides or inclusions present in the sample. The lower the DI, the higher the quality of the aluminium obtained, and it is calculated by determining the ratio between the density of the sample obtained in air (1 bar) and the density of the sample obtained at 5 mbar.

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Table 1: Densities of samples at atmosphere, 80 mbar, 5 mbar, and Density Index (DI) for vacuum and for dross test samples.

Quality	Weight air air (g)	Weight air water (g)	Weight DI air (g)	Weight DI water (g)	Weight t dross air (g)	Weight t dross water (g)	ρ atm	ρ vac	ρ dross	DI Vacuum	DI Dross
Crucible 1	49,50	31,21	62,94	38,95	67,47	40,71	2,71	2,62	2,52	3,06	6,8392
Crucible 2	66,98	42,09	58,34	36,26	56,88	35,27	2,69	2,64	2,63	1,81	2,1897
Crucible 3	53,03	33,36	65,31	40,63	57,18	35,39	2,70	2,65	2,62	1,84	2,6649
Crucible 4	60,81	38,25	71,11	43,94	70,46	43,44	2,70	2,62	2,61	2,90	3,2566
Crucible 5	73,10	45,98	71,99	45,01	95,57	59,23	2,70	2,67	2,63	1,01	2,4316
NG 1	61,17	38,48	60,84	37,82	55,77	32,80	2,70	2,64	2,43	1,97	9,9392
NG 2	57,91	36,27	65,60	41,01	69,31	40,69	2,68	2,67	2,42	0,31	9,5039
NG 3	67,45	42,39	63,16	39,58	66,00	40,55	2,69	2,68	2,59	0,48	3,6492
NG 4	66,90	42,15	61,50	38,52	66,88	38,27	2,70	2,68	2,34	0,99	13,5176
NG 5	58,69	36,94	71,60	44,60	65,96	40,93	2,70	2,65	2,64	1,72	2,3404
NG_12_1	52,03	32,22	58,29	33,02	75,12	46,72	2,63	2,31	2,65	12,17	-0,7089
NG_12_2	70,39	43,63	63,53	35,78	60,43	36,11	2,63	2,29	2,48	12,97	5,5365
NG_12_3	63,80	39,48	62,28	33,15	66,52	38,22	2,62	2,14	2,35	18,50	10,3999
NG_12_4	66,17	40,76	59,58	32,57	63,33	37,04	2,60	2,21	2,41	15,29	7,4956
NG_12_5	59,92	36,89	67,31	37,86	62,26	35,62	2,60	2,29	2,34	12,16	10,1750
H 1	68,93	43,17	63,59	35,45	64,30	38,36	2,68	2,26	2,48	15,55	7,3643
H2	65,30	40,85	47,82	27,12	66,72	40,47	2,67	2,31	2,54	13,50	4,8317
H3	59,10	36,76	55,56	31,22	69,99	41,05	2,65	2,28	2,42	13,71	8,5817
H4	61,40	38,38	64,11	36,79	62,58	34,55	2,67	2,35	2,23	12,02	16,2954
H5	49,19	30,76	53,10	30,09	63,03	33,55	2,67	2,31	2,14	13,54	19,8934

Generally, authors consider a metal quality of 0-3 as excellent and 10-15 as poor. Other authors indicate that 1 is the threshold for excellent casting quality. There is a high variation in the obtained sample DI. In the next table, the average DI for every quality is calculated.

Table 2: Average Density Index for dross and vacuum test samples.

Quality	DI average dross	DI average vacuum
Crucible	2,13	3,48
NG	1,09	1,09
NG 12 hours	14,22	14,22
H2	13,66	13,66

Observing the results, we can classify the obtained quality as excellent in the case of the material that comes from the facility (crucible) and the crucible heating with NG. However, in the case of the heating during 12h with NG and the heating with H2, the obtained quality can be classified as poor.

It can be also observed how the obtained values are very similar for the vacuum and dross tests, probably related with an absence of oxides and inclusions in the obtained samples. In the next figure we can observe the diagram of the variation in the obtained values for every test.

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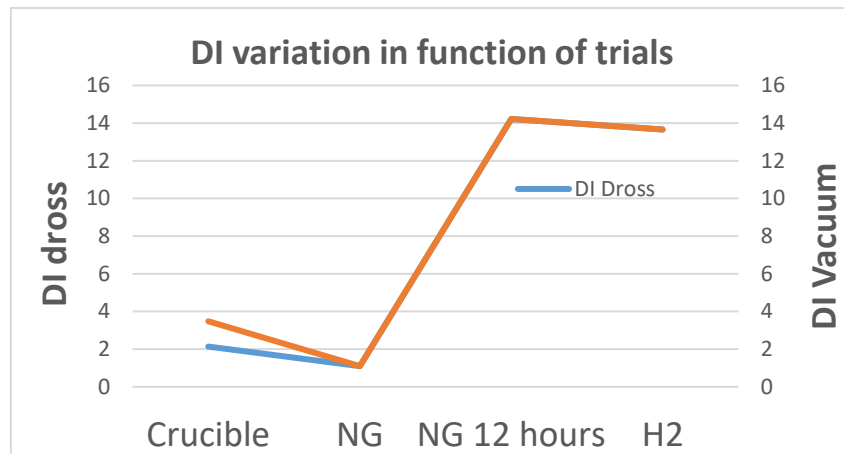


Figure 16: Variation of DI vacuum (80 mbar) and DI Dross (5 Mbar) in the trials.

2.3.3.2 K-Type sample analysis:

Ten K-type samples were obtained per test. We can observe in the figure the obtained samples per test.

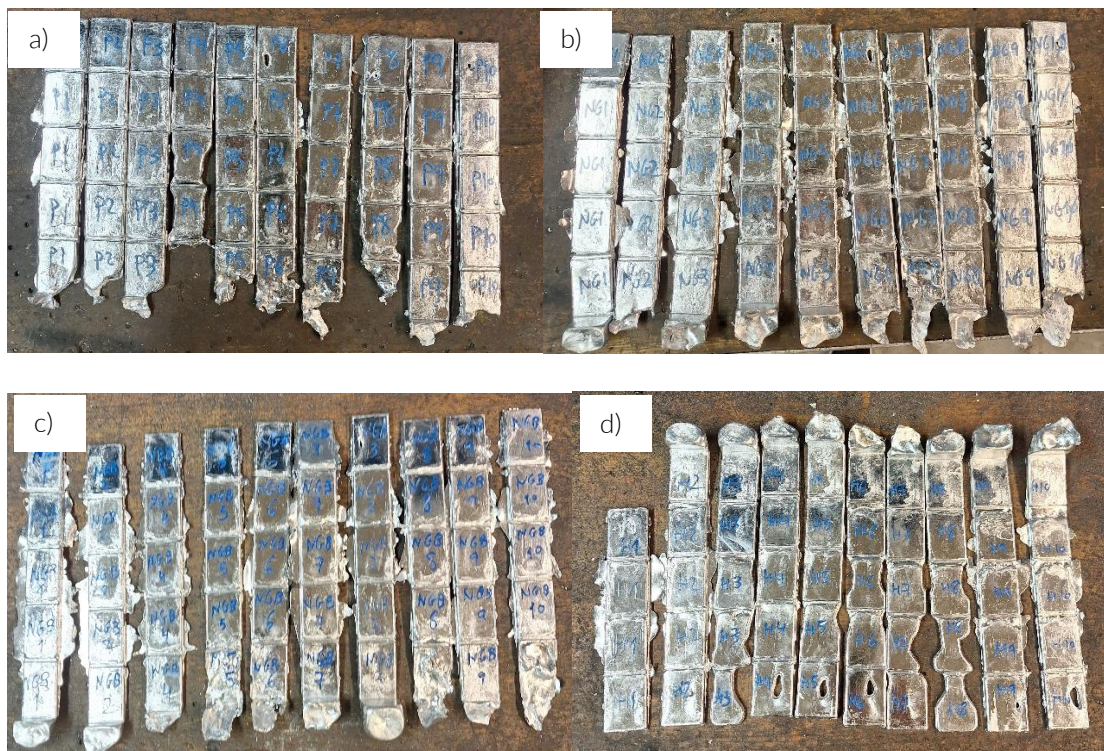


Figure 17: Test samples obtained in the K-type tests: a) Crucible; b) NG; c) NG after 12h; d) 100% H2.

The castability of the samples was good and quite similar in all the samples, with a little smaller in the case of the 100% H2 samples. This difference could be linked with the differences in the casting temperature of the samples, being the smallest in the case of the H2 samples, showing cold filling areas.

An analysis of the transversal areas of the samples was performed to determine the K-type index. In the next table we can observe the total amount of detected oxides in the transversal and the number of observed sections.

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Table 3: K-type index for different tests.

Quality	n	Nº. of surfaces analyzed	K-type index
Crucible	0	78	0,00
NG	0	78	0,00
NG 12h	2	78	0,03
100% H2	0	78	0,00

We can observe that only 2 small oxides were detected in the NG 12h sample, shown in the next picture.

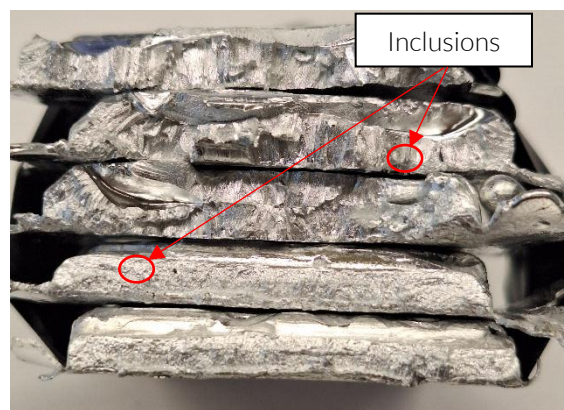


Figure 18: Oxides observed in NG 12h sample N°4.

Each company must define its own scale to characterise the quality of the metal obtained. The lower the value of "K", the higher the quality of the metal, with a value of "K=0" as a metal with excellent cleanliness. In many applications, a value of $K \leq 0.5$ is considered to correspond to a "clean" metal. The following table shows the values of the number of inclusions and the "K" coefficient. In the table they have been added the obtained samples in previous tests, to have more samples to compare.

Therefore, the value of "K" is less than 0.1, so it could be estimated that the K-Type quality is excellent. There is not a big variation between the different tests.

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2.3.3.3 Thermal analysis:

The obtained curves in the samples produced in the sand and steel cups were analyzed. In order to name the samples, GN1 were the samples produced in the first trial, GN2 the samples obtained after 12 hours of maintaining in the ladle and H the samples obtained in the H₂+O₂ trials. We can observe in the next two figures the obtained results for the different trials:

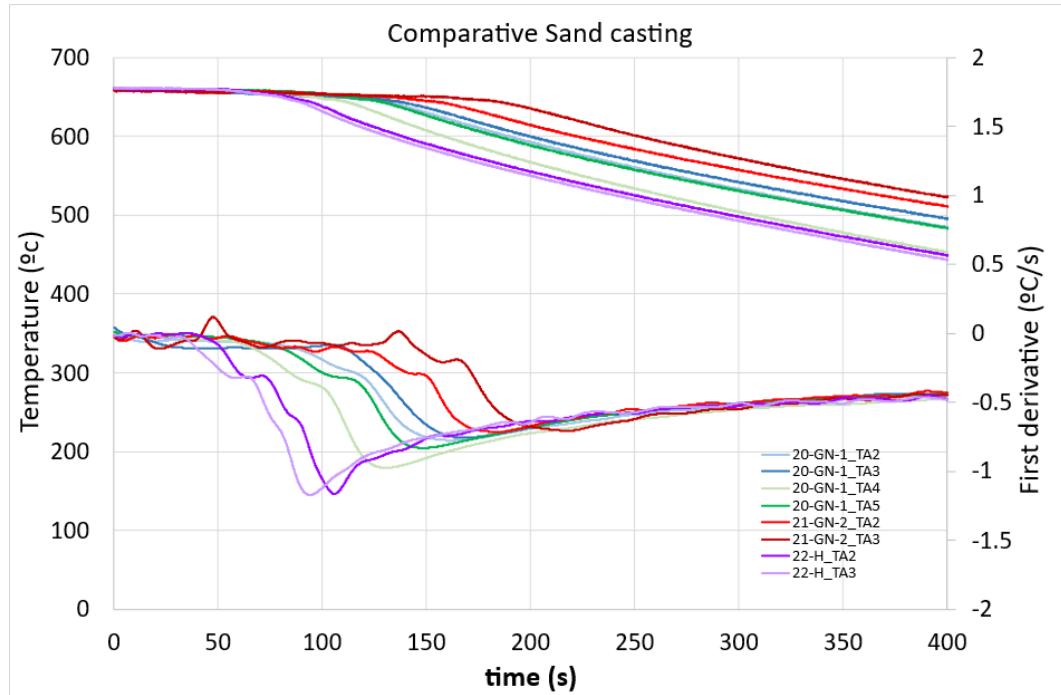


Figure 19: Analysis of sand cups tests for the different trials.

In sand cup testing and comparing between samples being poured at the same temperature (660-661.2°C), the samples with GN2 were the last to solidify (196 s at the temperature of 620°C). The samples with H₂, solidified earlier (a 54% reduction in time and 1% in temperature), and the samples with GN1 solidified with a 41% reduction in time, despite no significant temperature differences were observed (T^a solidus=620°C).

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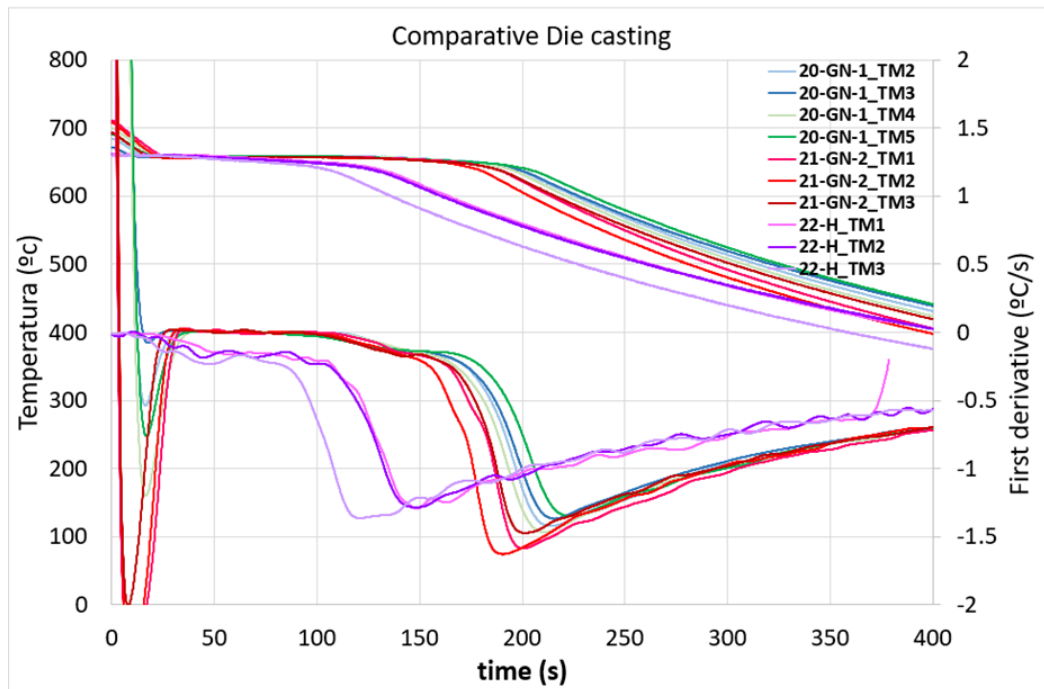


Figure 20: Analysis of steel cups tests for the different trials.

In the samples obtained in steel cups, and comparing samples poured at similar temperatures (662°C-693°C), the samples with GN2, despite being poured at the highest temperature (T^a pouring=693°C), displayed a comparable solidification time to the GN1 samples (175s for GN2 vs 190s for GN1).

Between samples GN1 and H2, the samples with H2, solidified earlier again (a 13% reduction in time), despite no significant temperature differences were observed (T^a solidus samples H2=613.4°C and T^a solidus samples GN1=611.6°C).

In general, it can be observed that there is not a big difference between the different obtained samples.

2.4 Conclusions

The next conclusions were obtained from the performed tests and analysis:

- The use of H₂ combustion and the maintenance of the molten metal heated for a long time with NG increases drastically the total amount of dissolved hydrogen in the molten metal. It's also well known that there is an increase of the H₂ content in the aluminium by increasing the metal temperature, the amount of water vapor in the atmosphere and by increasing the residence time at high temperatures.
- Using H₂ instead of NG results in lower consumption of the fuel required for preheating or maintenance of the ladle temperature. Care has to be taken with the adjustment of the burner power.
- The K-type test showed an excellent quality of the obtained samples, without oxides or inclusions, combined with a good castability. So, the use of H₂ didn't promote the generation of oxides or inclusions.
- The solidification curves were very similar, so no differences were detected between samples. The use of H₂ didn't promote modifications in the solidification properties.

3 Rotary furnace

3.1 Introduction

This demonstrator is a retrofitted rotary furnace for recycling aluminium in Befesa Valladolid, Spain.

The following targets are set for these tests:

- Evaluate the usage of an oxyfuel burner with NG and H₂ for a rotary furnace
- Metal quality: Metal quality: Equipment testing and trials with NG+H₂+O₂, first with 80% NG+20% H₂+O₂, Second with 100% H₂+O₂, third with 100%NG+O₂, fourth with 60% NG +40%H₂+O₂, fifth with 40% NG + 60% H₂+O₂ and sixth with 20%NG +80%H₂+O₂. Determination of metal yield and spent salt analysis.
- Combustion gases analysis: Equipment testing and trials. Use of pitot tubes to determine flow rates.
- Check safety procedures.

3.2 Scrap selection

Aluminum concentrates are obtained from the treatment and classification of salt slags or aluminum residues, where the metal fraction of higher purity is separated. They are presented as a granular material with a high metal content and a moderate proportion of salts and oxides. Although they can melt directly, they require the use of flux to minimize oxidation and maximize recovery.



Figure 21: Aluminum concentrates.

This material offers exceptional processability due to its physical and chemical properties. Its tendency to ignite inside the furnace is very low, even when excessive heat is applied, allowing for operation with a wider safety margin. In addition, it offers high and stable metal yield, which significantly reduces relative errors and provides virtually constant recovery values, with variations in the order of $\pm 3\%$. Added to this is the logistical advantage that the concentrates are produced directly at this facility, ensuring continuous availability and control over their quality. For these reasons, aluminum concentrates were selected as the primary material for the project's tests.

3.3 Combustion trials setup

To comprehensively evaluate the impact of hydrogen on the melting process—both in metallurgical and operational terms. A phased experimental plan has been designed to observe the system's behavior under different fuel ratios. This progressive approach facilitates the identification of trends, critical points, and potential nonlinearities in the behavior of the furnace and the material.



Figure 22: Befesa tilting rotary furnace.

To this end, a series of tests will be conducted in which the hydrogen fraction will be increased in a controlled manner from 0% to 100%. The increase will be made in 20% increments, so that each test represents a scenario clearly distinguishable from the previous one. This structure will allow for the comparison of key parameters such as:

- Metallic yield,
- Specific fuel consumption,
- Physical and chemical characteristics of the slag,
- Thermal stability of the process,
- Composition and behaviour of the emitted gases,
- And any observable variations in furnace operation.

The planned test sequence is as follows:

- Test 1: 0% H₂ – 100% natural gas
- Test 2: 20% H₂ – 80% natural gas
- Test 3: 40% H₂ – 60% natural gas
- Test 4: 60% H₂ – 40% natural gas
- Test 5: 80% H₂ – 20% natural gas
- Test 6: 100% H₂

This experimental design will allow us not only to quantify the effect of hydrogen on process performance and efficiency, but also to identify potential operational limitations, necessary adjustments to melting parameters, and any emerging behavior that could influence the industrial viability of using hydrogen as the primary fuel.

The detailed study of all variables involved will not be conducted entirely by our team, as this project is being carried out in collaboration with various entities that will actively participate in data collection and sample acquisition during the different stages of the smelting process. Each collaborator will contribute their specific expertise to ensure a comprehensive and multidisciplinary analysis of the results.

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Befesa will be responsible for determining:

- Metal yield: This will be calculated internally using the ratio of the weight of the recovered metal to the weight of the charged material (900 kg), allowing for an assessment of the process's metallurgical efficiency.
- Fuel consumption: The furnace is equipped with flow meters that record, in real time, the volumes of oxygen, hydrogen, and natural gas supplied to the burner. This data will provide the information needed to analyze specific consumption rates and their variation between tests.
- Physical and chemical characteristics of the slag: The slag generated will be studied at the pilot plant, where parameters such as particle size distribution, bulk density, chemical composition, and behavior during processing will be evaluated.
- Metal characteristics: Representative samples of the obtained aluminum will be taken to perform chemical composition tests and verify the presence of trace elements or variations associated with the type of fuel used.

The analysis of the remaining parameters—including the operational stability of the process, the thermal dynamics of the furnace, and the detailed composition of the emitted gases—will be carried out by other project collaborators, who will contribute their results to complete the overall interpretation of the study.

3.4 First campaign of tests

During the first test campaign, various operational limitations were identified that required adjustments to the initially planned experimental sequence. It was not possible to carry out “Test 1.2,” since when attempting to feed the burner with a mixture containing 20% hydrogen, the system exceeded the safety thresholds configured in the furnace control system. This deviation triggered the automatic activation of the safety mechanisms, causing the burner to shut down immediately and, therefore, making it impossible to continue the test.

Despite this limitation, the testing campaign proceeded normally for the remaining planned points, allowing us to obtain an initial understanding of the process behavior under different hydrogen concentrations. The tests ultimately conducted were as follows:

- Test 1.1: 0% H₂ – 100% natural gas
- Test 1.2: 20% H₂ – 80% natural gas
- Test 1.3: 40% H₂ – 60% natural gas
- Test 1.4: 60% H₂ – 40% natural gas
- Test 1.5: 80% H₂ – 20% natural gas
- Test 1.6: 100% H₂

The following section presents a summary table with the main results obtained. All recorded data - including graphs, process files, flow records, and operational observations - is available in the folder corresponding to this project on the server, organized by test to facilitate consultation and subsequent analysis.

Table 4: First campaign results

Test	Theoretical % H ₂	Yield	NG Vol. (m ³)	H2 Vol. (m ³)	Actual % H2	Power consumption (kW/t)	Sink time (min)	Melting time (min)
1.1	0	66%	33.5	0.0	0%	372.22	43	69
1.2	20							
1.3	40	68%	17.4	39.00	39%	316.83	39	70
1.4	60	67%	10.9	55.90	59%	298.13	32	57
1.5	80	68%	4.7	71.20	81%	277.69	29	57
1.6	100	67%	0	73.33	100%	232.21	30	54

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Analysis of the results obtained during the first campaign confirms, as a first relevant observation, that the system's behavior corresponds exactly to what was predicted from a thermodynamic standpoint. As the proportion of hydrogen in the fuel mixture increases, the flow rate of natural gas decreases progressively, while the flow rate of hydrogen increases in direct proportion. This trend is explained by the fact that the calorific value of hydrogen is approximately three times lower than that of natural gas, which forces the system to supply a considerably larger volume of hydrogen to maintain the same energy input to the fusion process. As a result, the total flow rate supplied to the burner increases steadily as the fraction of hydrogen used increases.

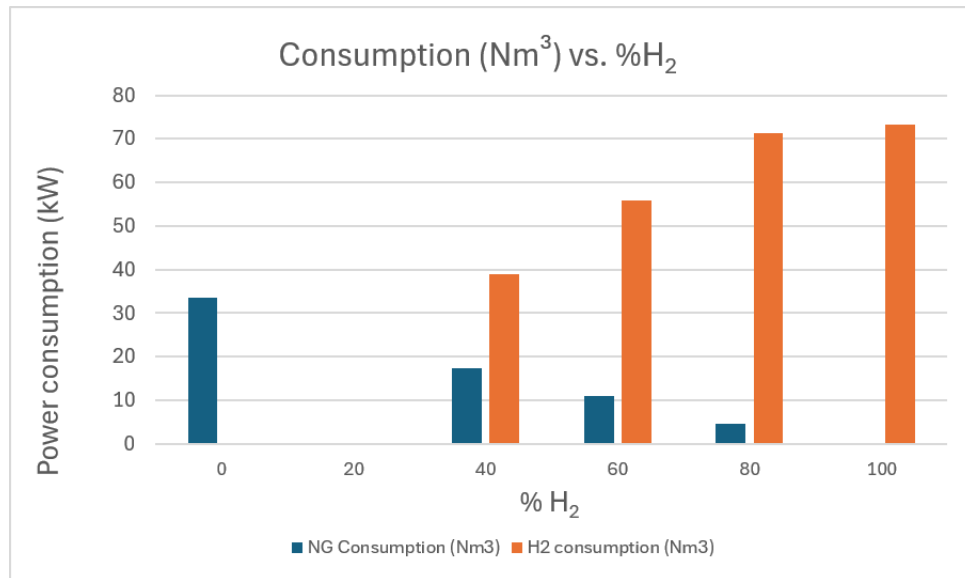


Figure 23: Consumption of each gas versus theoretical %H₂.

Continuing with the analysis, when the volumes of gases used are multiplied by the calorific value of each gas, it is observed that the empirical percentage ratio of gases corresponds to the theoretical one, confirming the stability of the control system under all evaluated conditions.

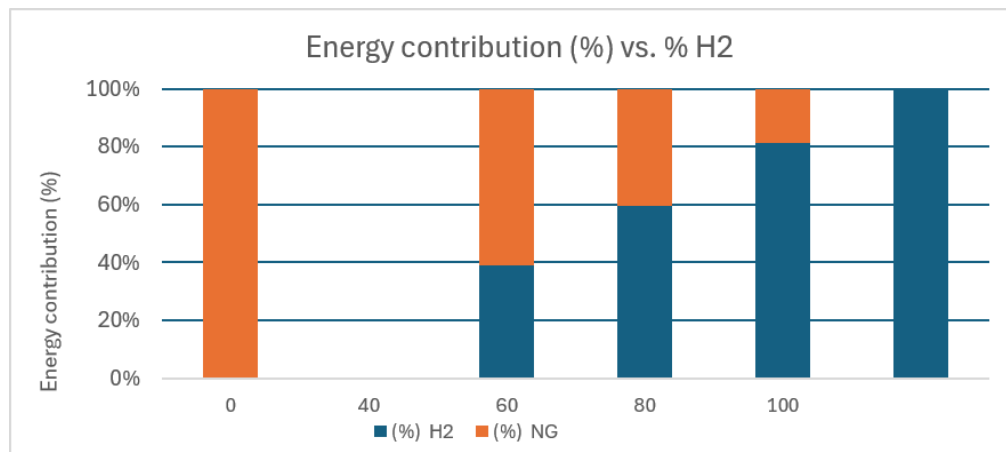


Figure 24: Percentage of energy contributed by each gas.

On the other hand, it has been observed that energy consumption per ton of raw material fed into the furnace decreases immediately as soon as small percentages of hydrogen are incorporated into the fuel mixture. This behavior is particularly striking when one considers that, in principle, the energy supplied by the burner should remain practically constant regardless of the fuel composition, since this is the design parameter. The observed reduction therefore suggests that the presence of hydrogen would improve the thermal efficiency of the process, possibly due to more homogeneous combustion, greater heat transfer capacity, or more effective energy distribution within the melting chamber.

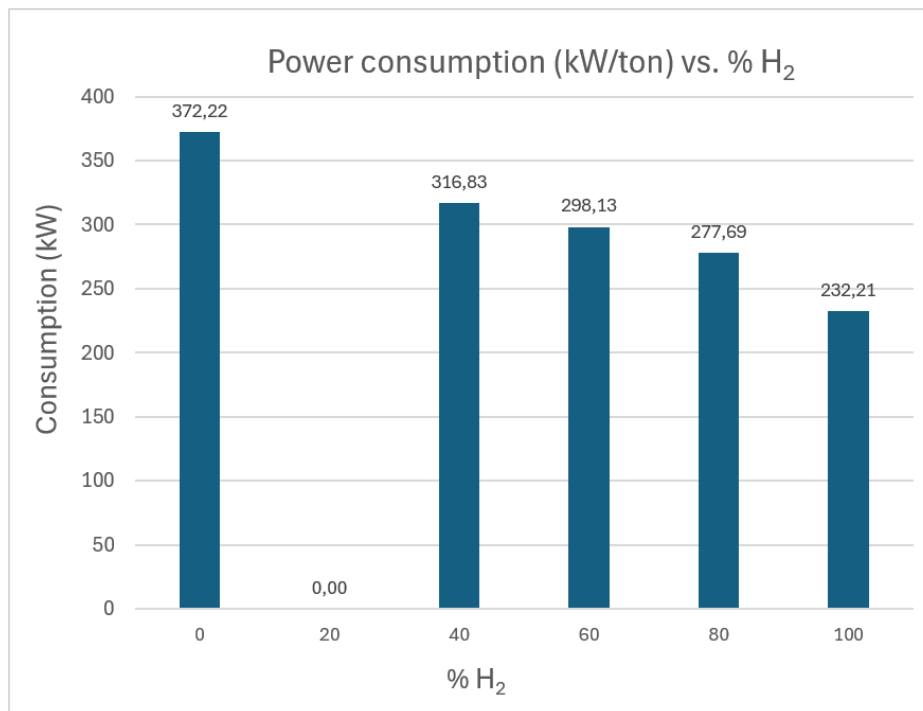


Figure 25: Figure 23: Power variation as a function of %H₂

Another noteworthy aspect, consistent with previously observed trends, is that the reduction in energy consumption per ton of processed material is accompanied by a decrease in the operating time required to complete each melting cycle. This correlation points to an overall improvement in the thermal efficiency of the process. Everything indicates that hydrogen combustion promotes more efficient heat transfer and a faster thermal response within the furnace, allowing for shorter melting times without negatively affecting metal recovery. Taken together, these results reinforce the hypothesis that hydrogen not only modifies the nature of energy input but also optimizes the internal dynamics of the melting process.

These results generated particular interest because, as previously mentioned, they were not consistent with the burner design, which was intended to supply a virtually constant power output by adjusting only the flow rates of the different fuels. Although replacing natural gas with hydrogen can introduce variations in the process—such as changes in flame shape, shifts in the predominant heat transfer mechanisms (from convection to radiation), or other secondary effects that have not yet been fully characterized—the observed difference, on the order of 130 kW/ton between the evaluated extremes, was too significant to be attributed solely to these factors.

3.5 Second campaign of tests

In light of this discrepancy, a thorough review of the formulas and parameters used for the gas feed was conducted, identifying an error in the values provided by the supplier, which in turn had led to an incorrect configuration in the furnace control system. At the same time, the issue preventing the test from being conducted with 20% hydrogen was also resolved. The detection of this deviation, along with the correction of the associated problems, allowed us to move forward with a second round of tests under properly adjusted operating conditions and with greater reliability in the data obtained.

The second campaign will consist of the following tests:

- Test 3.1: 0% H₂ – 100% natural gas
- Test 3.2: 20% H₂ – 80% natural gas
- Test 3.3: 40% H₂ – 60% natural gas
- Test 3.4: 60% H₂ – 40% natural gas
- Test 3.5: 80% H₂ – 20% natural gas
- Test 3.6: 100% H₂

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NOTE: The tests corresponding to the first campaign are identified as 1.X, while those from the second campaign appear as 3.X. This is because, between the two campaigns, an additional series of tests (2.X) was conducted in which the operating procedures differed from those established for the project. During these intermediate tests, external collaborators required sampling over extended periods, which significantly altered the process conditions and, consequently, affected the comparability of the results. For this reason, it was decided to exclude the 2.X series from this analysis to maintain methodological consistency and the validity of the conclusions.

Table 5: Second campaign results

Test	Theoretical % H2	Yield	NG Vol. (m³)	H2 Vol. (m³)	Actual % H2	Power consumption (kW/t)	Sink time (min)	Melting time (min)
3.1	0	58%	40.20	0.00	0%	446.67	50	70
3.2	20	63%	32.20	28.40	20%	447.71	52	72
3.3	40	67%	25.30	48.50	35%	434.69	45	76
3.4	60	59%	15.90	81.50	59%	434.75	48	71
3.5	80	61%	8.80	103.70	77%	426.16	44	74
3.6	100	67%	0.00	138.20	100%	437.63	44	98

After analysing these results, it is confirmed once again that the energy calculation obtained by multiplying the volumes of gas consumed by the corresponding calorific value aligns reasonably well with the expected theoretical values. However, a discrepancy of approximately $\pm 5\%$ persists, although this is smaller than that observed in the previous campaign. This improvement indicates that the corrections implemented in the system configuration have significantly reduced the margin of error, allowing for a more reliable correlation between recorded consumption and the energy actually supplied to the process.

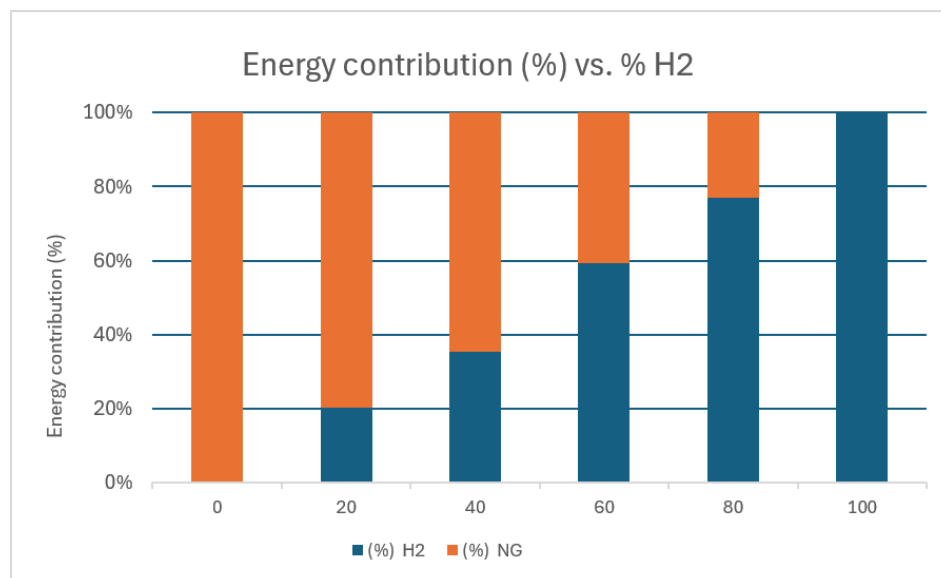


Figure 26: Percentage of energy supplied by each gas.

When analyzing the data on power required per fusion in this second campaign, it is evident that the downward trend observed previously has completely disappeared. The resulting trend shows much more stable behavior, with fluctuations between fusions remaining within an approximate range of ± 20 kW, which is equivalent to a relative deviation of approximately $\pm 5\%$. This greater uniformity confirms that the corrections implemented in the system configuration have enabled a more consistent and reproducible energy supply between experiments, reinforcing the reliability of the results obtained.

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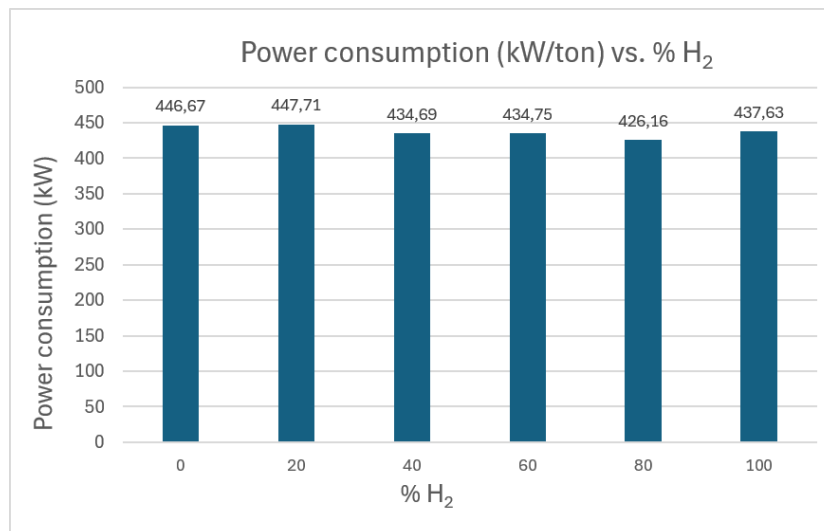


Figure 27: Power consumption per ton for second campaign

When comparing the results of both campaigns, the disappearance of the downward trend initially observed is clearly evident, placing the new data much closer to the theoretical behavior expected for a burner operating at nearly constant power. Furthermore, an increase is observed in the power required to melt the same amount of metal, which reinforces the hypothesis that the values recorded during the first test run were affected by configuration errors and showed significant deviations from the furnace's actual operating conditions. The following graph illustrates this difference: the red dotted line shows the downward trend obtained in the first campaign, while the green dotted line reflects a much more stable trend consistent with constant power.

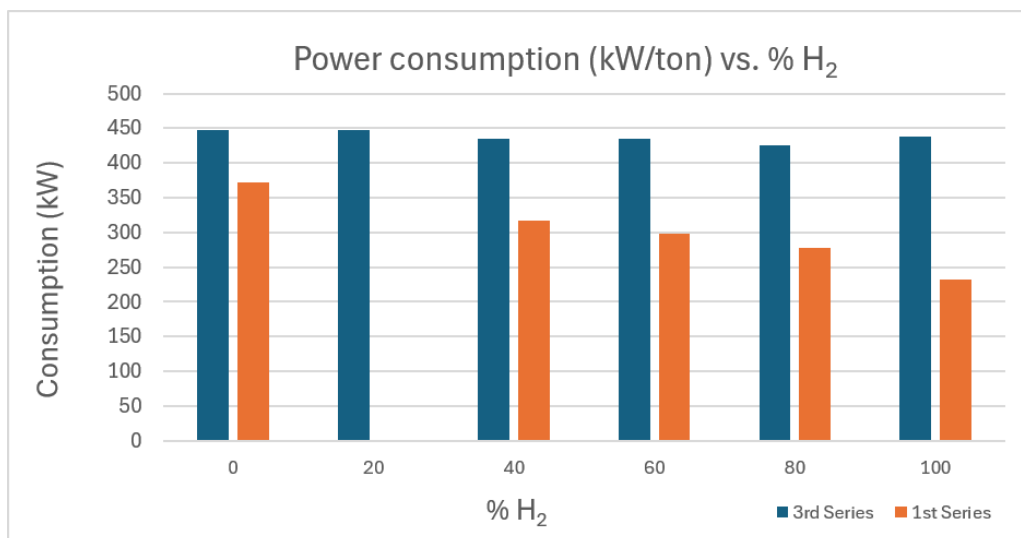


Figure 28: Power consumption for both campaigns

3.6 Exhaust gas analysis

To determine the exhaust flow in the filter system and compare it with the combustion gases consumption, 2 different pitot tubes were installed in the connection tube of the chimney and the filter, just before entering the filter and after the dilution valve.

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Figure 29: Details of installed pitot tubes and register

In the next diagram, we can observe the registration of the pressure, speed, and flow.



Figure 30: Measurement example with a pitot tube

As can be observed, the measurements and flow are stable, and the flow can be monitored in the exhaust gas system. The measurements confirm the 7.500 m³/h and 15.000 m³/h of gas flow in the filter.

3.6.1 Exhaust gas composition:

The analysis of the gas composition has been completed. A calculation of the total amount of external air that entries into the furnace has been performed with the obtained data, leaving out the calculations with a high % of H₂ (>80%), due to the fact that the measurement of CO₂ is done with an IR sensor, and it is not prepared to measure in high water vapor concentrations.

We can observe the different test data in Annex 1, with a difference between taking the data from the chimney or before the entry of the filter. The different phases of the process are detected in the analysis of the gases, and they have been correlated. More in concrete, we can observe the analysis of Test #1.

- Test #1: 20%H₂+O₂+80%NG.

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We can observe in the next figure the different stages of the combustion and the gas composition registered values in the chimney.

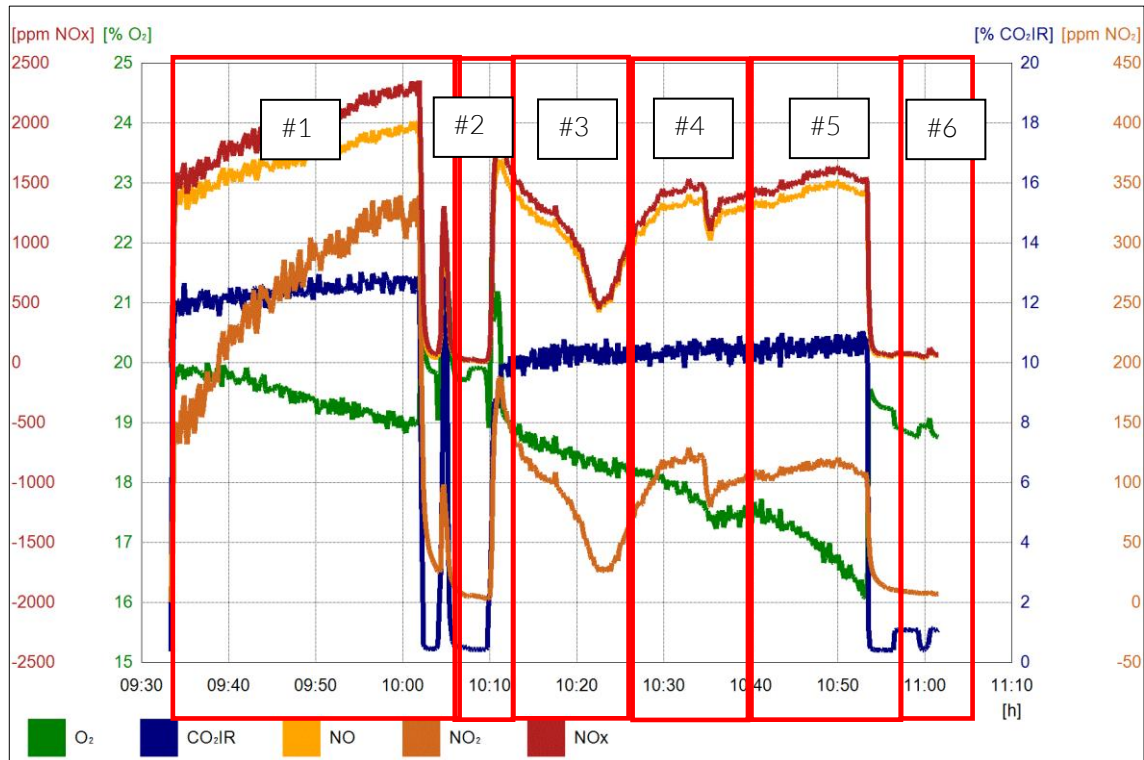


Figure 31: Test #1 20%H2+O2+80%NG profile in the chimney

1. Preheating of the furnace with NG+O2.
2. Charge of material. 2 steps.
3. Starts of melting with 80%NG+20%H2+O2. Emissions decrease as the cold charge reduces the furnace temperature.
4. The temperature of the charge starts to increase, increasing emissions.
5. The temperature of the charge starts to increase, increasing emissions.
6. The gas sensor equipment is moved from the furnace to the filter.

We can observe in the next diagram the different stages of the combustion and the gas composition registered values in the filter tube.

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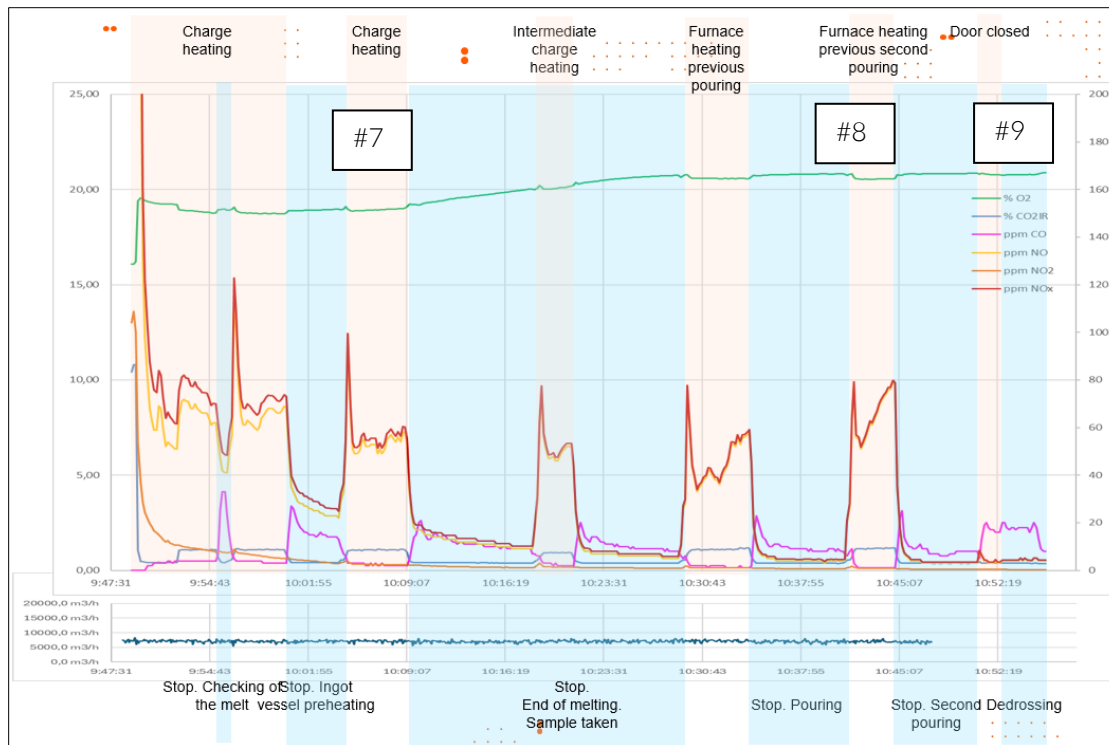


Figure 32: Test #1 20%H2+O2+80%NG profile in the filter tube

7. Finishing the melting.
8. First pouring.
9. Second pouring.

In the next table, we can observe the approximative combustion gases analysis in mg/MJ measured in the filter in the melting process:

Table 6: Approximate combustion gases composition analysis comparison in mg/MJ (wet)

Melting	NO	NO2	NOx
	mg/MJ (wet)	mg/MJ (wet)	mg/MJ (wet)
100% NG	1,86	0,23	2,09
80% NG 20%H2	1,74	0,06	1,80
60% NG 40%H2	1,79	0,02	1,82
40% NG 60%H2	1,72	0,00	1,73
20% NG 80%H2	1,85	0,00	1,85
100%H2	1,28	0,00	1,28

In the next figure, we can observe how the amount of NOx increased near lineally by increasing the % of H2 in the combustion mix.

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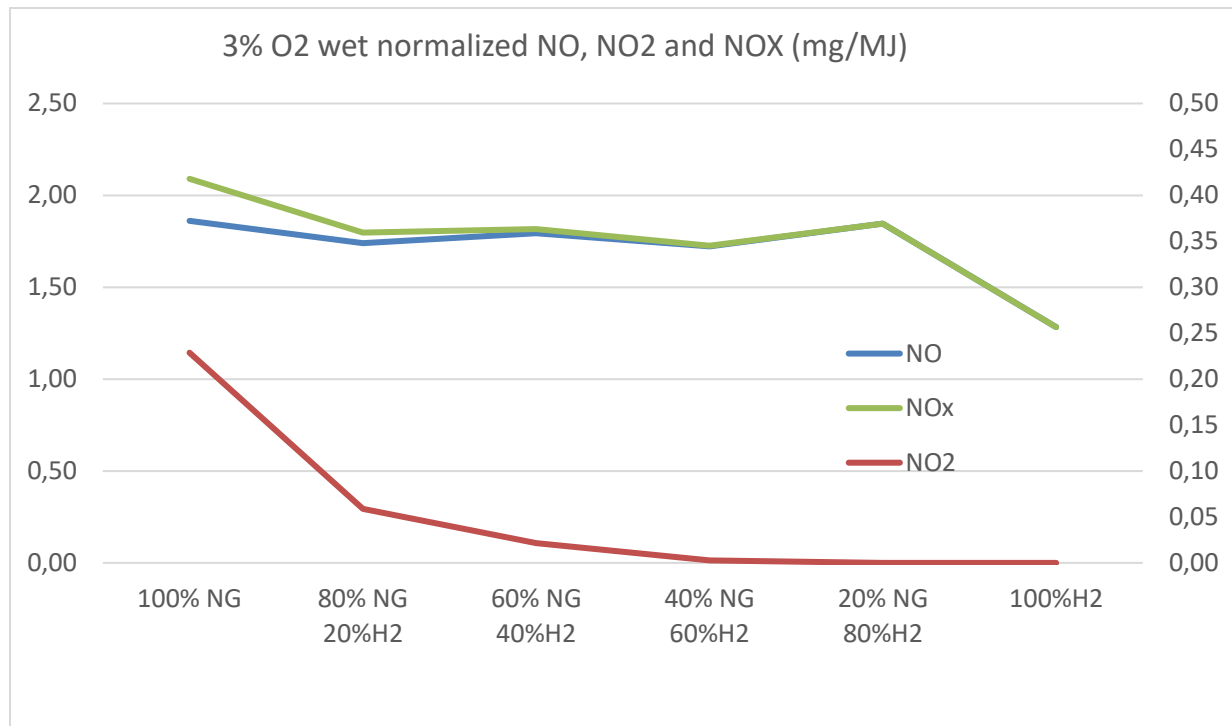


Figure 33: NO, NO2 and NOx variation in function of the % of H2 in the combustion mix

We can observe a slight decrease in the emissions with an increase with the %H2, probably due to the decrease in the applied power and the higher emissivity of H2+O2 combustion over 1,200 °C.

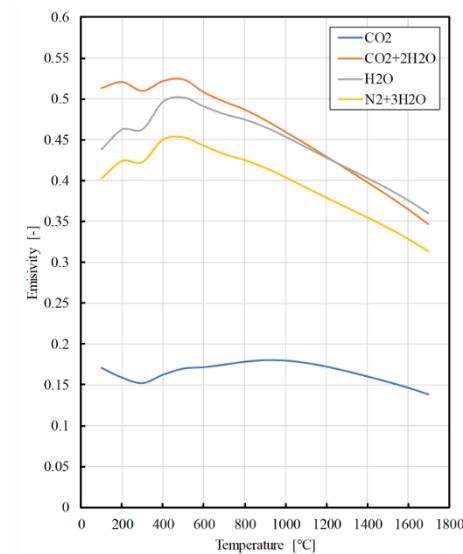


Figure 34: NO, Emissivity in function of the combustion system and temperature (Source: Nippon Gases)

3.6.2 Conclusions

From the trials, some conclusions have been obtained:

- The continuous analysis of the flue gases composition could allow determining the different phases of the preheating, melting, pouring, and cleaning and controlling the furnace.
- When the % of H2 is higher than around a 70%, the measurement of CO2 by IR gives not correct values and regulates the furnace.

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- The gas analysis at the entry of the filter allows control of the process, employing standard gas analyzers, due to the high dilution of gases. Many standards for industrial processes established the point of measurement in the emission point, corresponding in this case with the filter exhaust tube.
- The change in the gas flow of the filter must be considered, because the higher the flow, the higher the dilution. The normalization to 3% O₂ takes it into account.
- The percentage of NO_x in the process varies in function of the furnace inside temperature. The higher the temperature, the higher the NO_x values. It is observed that a decrease in the temperature of the furnace is observed after the scrap is charged, and a consecutive increase when the metal is melted.
- Employing 100% of H₂ instead of 100% of NG decreases the NO_x measured values. The results obtained are under the legal values admitted for aluminium foundries.

3.7 Aluminium quality analysis:

To determine the quality of the obtained aluminium in function of the employed combustion atmosphere, different equipment has been employed.

To characterise the quality of the aluminium, different control systems were used: the K-Type mould, the dross test (including calculation of the sample density), and the thermal analysis.

For the determination of the density index (DI) and the dross test index, a Martech VTCM0017 vacuum equipment was employed, which includes a hydrostatic balance. The following figure shows an example of the equipment.



Figure 35: Vacuum equipment and scale model Martech VTCM0017

Another way to determine the aluminium quality is employing the K-Type test, which determines the quality in function of the total inclusions or oxides determined in the observation areas and the total number of analyzed areas and it also gives an idea of the fluidity of the alloy.

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Figure 36: K-mold test equipment and obtained samples.

The computer-assisted thermal analysis (TA) studies the solidification path of an aluminium molten sample, determining the main solidification characteristics and also the presence of porosity.



Figure 37: TA test equipment and obtained samples.

3.7.1 Aluminium quality determination:

The dross-test equipment to obtain the reduced pressure samples is based on the capacity of determining the H₂ content in aluminium in function of the density and the applied under-pressure in the test. If the pressure is reduced to 1/100th of an atmosphere, it is expected that the residual air layer between the oxide films would be expanded by approximately 100 times, and so may be rendered visible. In the next figure we can observe the relation between the pressure, the density, and the hydrogen content.

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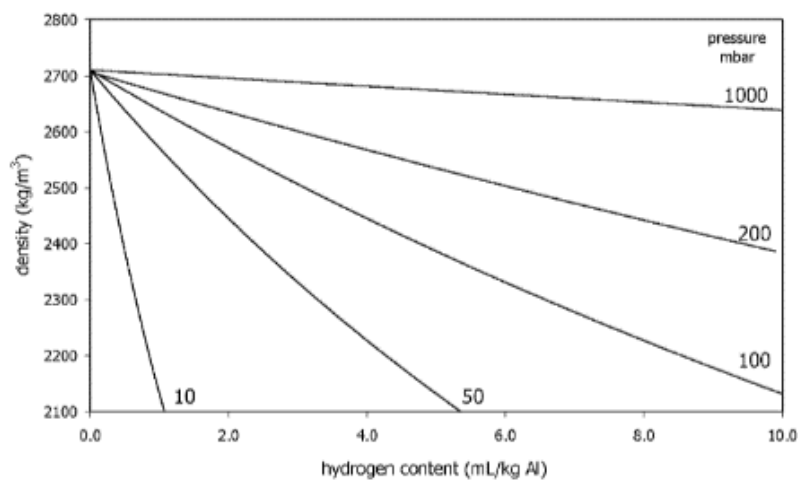


Figure 38: Relation between density, test pressure, and hydrogen content aluminium

We analyzed the specimens obtained in the dross-test equipment:

Table 7: Relation between density, test pressure, and hydrogen content aluminium.

		Test pressure		
		Ambient	80 mbar	5 mbar
Burner fuel composition	100% NG			
	40% H2 – 60% NG			
	100% H2			

The DI value corresponds to the Density Index (DI), which is used to define the quality of the material according to the oxides or inclusions present in the sample. The lower the DI, the higher the quality of the

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aluminium obtained, and it is calculated by determining the ratio between the density of the sample obtained in air (1 bar) and the density of the sample obtained at 5 mbar. In the next table, there are included the results of the previous trials at BEFESA VALLADOLID.

Table 8: Densities of samples at atmosphere, 80 mbar, 5 mbar, and Density Index (DI)

Quality	ρ atm	ρ vac	ρ dross	DI
NG+O2_3_1	2,71	2,69	2,60	0,77
NG+O2_3_2	2,70	2,55	2,64	5,58
NG+O2_3_3	2,69	2,71	2,14	-1,04
NG+O2_3_4	2,67	2,38	2,39	10,77
40%H2_1	2,68	2,66	2,65	0,78
40%H2_2	2,69	2,68	2,62	0,32
40%H2_3	2,71	2,67	2,63	1,68
100%H2_1.1	2,71	2,72	2,58	-0,37
100%H2_1.2	2,70	2,69	2,35	0,45
100%H2_1.3	2,72	2,66	2,46	2,22
100%H2_2.1	2,71	2,68	2,67	1,02
100%H2_2.2	2,71	2,63	2,52	2,91
100%H2_2.3	2,70	2,65	2,41	1,86
20%H2_1	2,69	2,59	2,59	3,62
100%H2_2	2,68	2,58	2,49	4,05
100%NG_3	2,69	2,63	2,56	2,23
40%H2_4	2,69	2,66	2,52	1,26
60%H2_5	2,70	2,66	2,52	1,41
80%H2_6	2,71	2,70	2,69	0,49

Generally, authors consider a metal quality of 0-3 as excellent and 10-15 as poor. Other authors indicate that 1 is the threshold for excellent casting quality. There is a high variation in the obtained sample DI. In the next table, the average DI for every quality is calculated.

Table 9: Average Density Index (DI)

Quality	DI average dross	DI average vacuum
NG+O2	3,66	8,33
20%H2+O2+80%NG	3,62	3,57
40%H2+O2+60%NG	1,01	3,28
60%H2+O2+40%NG	1,41	6,61
80%H2+O2+20%NG	0,49	0,79
100%H2+O2	1,73	7,63

The preliminary analysis shows that there is good for 100% of NG+O2 and a 20%H2+O2+80%NG. Employing higher amounts of H2 promotes an increase in the quality to an Excellent level. So, better K-type quality results are obtained in H2+O2 combustion samples.

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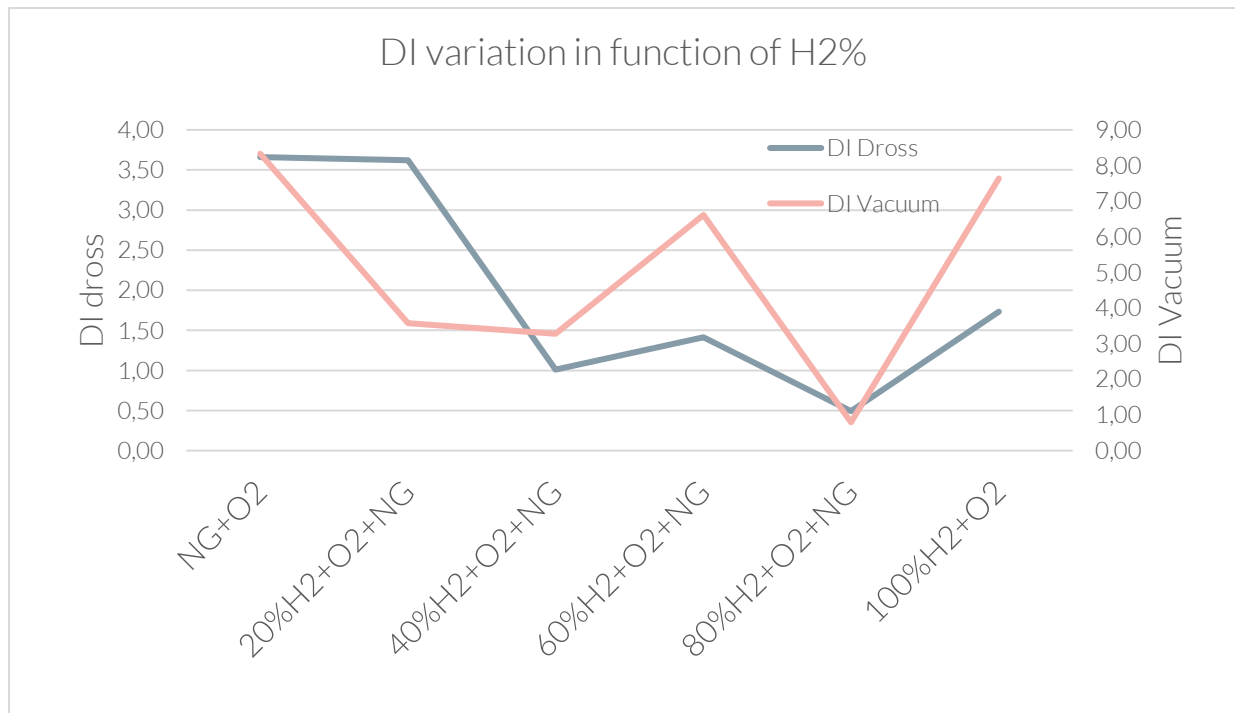


Figure 39: Variation of DI vacuum (80 mbar) and DI Dross (5 Mbar) in function of H2%



Figure 40: Photos of the K-Type probe. Samples obtained in April 2025

Variability in the filling of the moulds has been observed, with complete filling in some cases, but more related to the temperature of the mold, metal temperature or pouring time in the pouring of the molten metal in the die. The castability is therefore acceptable. In the K-Type test, the way to characterise the quality according to the number of inclusions in the test areas and the way to obtain the observation areas should be defined. The cross sections of the K-type samples are shown below.

The metal cleanliness value is expressed as the K-mold (K) value. This value is based on visual inspection of the broken surface of the parts and determination of the number of inclusions on the surface to determine the degree of cleanliness of the sample.

$$K = S/n$$

K - total number of inclusions in a sample piece on the fracture surface.

S - total number of inclusions determined on n-analyzed fracture surfaces.

n - total number of samples.

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In the next figure, we can observe an inclusion in the analyzed area of a sample.



Figure 41: Detail of an inclusion in the analyzed area

Each company must define its own scale to characterise the quality of the metal obtained. The lower the value of "K", the higher the quality of the metal, with a value of "K=0" as a metal with excellent cleanliness. In many applications, a value of $K \leq 0.5$ is considered to correspond to a "clean" metal. The following table shows the values of the number of inclusions and the "K" coefficient. In the table they have been added the obtained samples in previous tests, to have more samples to compare.

Table 10: Determination of the number of inclusions per sample

Sample	n	Nº. of surfaces analyzed	K
NG+O2	5	162	0,03
20%H2+O2+NG	1	26	0,04
40%H2+O2+NG	1	133	0,01
60%H2+O2+NG	0	21	0,00
80%H2+O2+NG	0	28	0,00
100%H2+O2	9	241	0,04

Therefore, the value of "K" is less than 0.1, so it could be estimated that the quality is excellent. There is not a big variation between the different tests.

3.7.2 Thermal analysis:

At least 4 different TA's have been performed for each of the studied conditions. In the next diagram, we can observe the comparison between the average curve of each condition.

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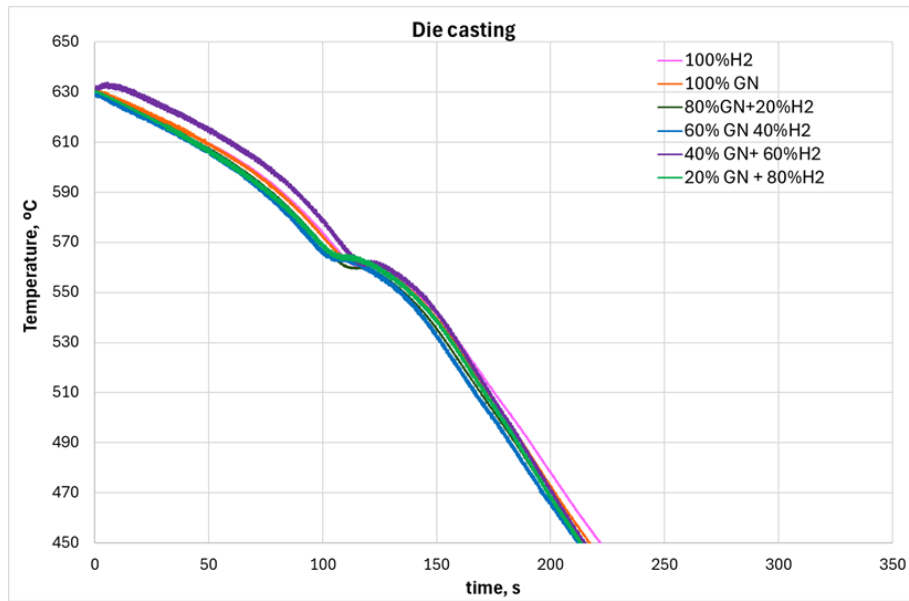


Figure 42: Detail of mean solidification curves

It can be observed that there is a slight difference between the solidification curves, but they remain quite similar. The small differences in the solidification times could be related to the different final alloy composition.

We can observe in detail the obtained solidification parameters in the next table.

Table 11: Main solidification temperatures (°C) in sand test cups

Sand test cups	Max.	Liq. Nucl.	Max. Liq.	Liq. Recal.	Nucl. Eut.	Max. Eut.	Eut. Recales.	Inter m start	Inter m. End	Solidus
100% NG	627	622	615	0	613	604	0	569	561	521
80% NG 20% H2	629	625	621	0	617	606	0	566	558	526
60% NG 40% H2	622	616	606	0	609	600	0	568	559	521
40% NG 60% H2	624	620	615	0	611	602	0	566	559	518
20% NG 80% H2	619	-	-	-	611	599	0	568	561	524
100% H2	625	621	616	0	610	604	0	567	558	522

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Table 12: Main solidification temperatures (°C) in steel test cups

Steel test cups	Max.	Liq. Nucl.	Max. Liq.	Liq. Recal	Nucl. Eut.	Max. Eut.	Eut. Recales	Inter m start	Inter m. End	Solidus
100% NG	641				628,3	626,3	0	575,4	561,8	513,4
80% NG 20% H2	674,7	648,4	634	0	630,9	625	0	570,9	560	518,3
60% NG 40% H2	634,5							571,8	562,2	518
40% NG 60% H2	633,9				625,3	624,7	0	571,8	560,5	513
20% NG 80% H2	631,1				624	621,1	0	577,3	562,4	515,7
100% H2	653,8	633,4	633,3	0	630,2	626,4	0	571,9	560,2	516,9

3.8 Conclusions

We describe the obtained conclusions:

- There is a noticeable lower energy consumption when hydrogen is used as the main fuel for the melting process instead of natural gas, around 5% less.
- It has been observed that it is possible to control the combustion process by continuous gas analysis monitorization.
- The gas analysis at the entry of the filter allows the control of the process, employing standard gas analyzers at the emission point.
- It has been observed that there is a slight decrease in emissions with an increase with the %H2, probably due to the decrease in the applied power and the higher emissivity of H2+O2 combustion over 1,200 °C.
- The percentage of NOx in the process variates in function of the furnace inside temperature. The higher the temperature, the higher the NOx values.
- Density and dross Index quality is good for 100% of NG+O2 and a 20%H2+O2+80%NG and higher amounts of H2 promotes an increase in the quality to an Excellent level.
- K-type test "K" is less than 0.1, so it could be estimated that the quality is excellent for all the samples without a significative variation.
- There is a slight difference between the solidification curves, but they remain very similar. There is no recalescence in the liquid nor in the eutectic points (good refining and modification of the aluminium structure).

4 Reverberatory melting furnace

4.1 Introduction

The work presented in this chapter focuses on the industrial-scale demonstrator operated at the Constellium Technology Centre (C-TEC). This demonstrator consists of an oxyfuel aluminum reverberatory furnace designed for flexible operation with natural gas, hydrogen, and their blends. A detailed description of the furnace, its retrofit, and its instrumentation is provided in Deliverable D5.1 and is not repeated here.

The experimental campaigns were conducted under representative industrial conditions over the period 2024 to 2025. The objective was to generate a comprehensive dataset covering different operating regimes and fuel compositions, to assess the behavior of the furnace when substituting natural gas with hydrogen.

This report presents the main results obtained on the C-TEC demonstrator, with a focus on key performance indicators relevant to industrial operation. These include thermal performance, dross formation, metal quality, and NO_x emissions. The analysis is based on industrial datasets and emphasizes robust trends rather than small variations, given the inherent variability of the process.

In addition to the experimental results, the deliverable also includes a modelling component based on a combination of simplified transient models and CFD simulations. This modelling work provides complementary insights into the thermal behavior of the furnace and the impact of hydrogen on heat transfer and combustion characteristics.

Overall, this deliverable aims to provide a comprehensive and industrially relevant assessment of hydrogen use in oxyfuel aluminum remelting furnaces, contributing to the evaluation of its technical feasibility within the HyInHeat project. The following targets are set for these tests:

- Evaluate the usage of an oxyfuel burner with NG and H₂ for a reverberatory melting furnace.
- Study the thermal performance of the furnace.
- Analyze the metal quality of the molten aluminium and the generated dross.
- Determine the emissions when switching fuels.
- Validate a CFD analysis based on the furnace.

4.2 Description of the experimental campaigns

The experimental campaigns were carried out at the Constellium Technology Centre (C-TEC) on the industrial reverberatory furnace demonstrator described in Deliverable D5.1. Only the key elements required to understand the results are recalled here.

The tests were performed under representative industrial conditions, with successive melting–casting cycles carried out continuously without complete furnace cooldown. Each melting cycle was initiated immediately after the previous casting operation, with the furnace typically at a temperature of approximately 750 °C, as measured by the roof thermocouple.

After opening the furnace door, approximately 10.7 t of aluminum at ambient temperature were charged into the furnace. The door was then closed, marking the beginning of the melting phase. The burner was operated at high and nearly constant thermal input during the first part of the cycle in order to rapidly heat both the furnace structure and the aluminum charge. Under typical low-power operating conditions, a constant thermal power of about 1.4 MW was applied for approximately 2.5 hours.

Once the roof temperature reached its target value (typically around 1000 °C under low-power conditions), the burner power was progressively reduced in order to maintain this temperature during the remaining part of the melting phase, typically around 1.5 hours. This phase ensures the completion of melting while avoiding excessive overheating of the furnace.

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The molten aluminum bath temperature is not measured from the beginning of the cycle. The thermocouple is inserted only once a sufficient amount of liquid metal has formed, typically after about 3 hours of operation. From this point, the bath temperature increases from the end of the phase change plateau, around 660 °C (corresponding to the melting temperature of aluminum), up to the target liquid aluminum temperature of approximately 720 °C. This temperature defines the end of the melting phase considered in this study.

As shown in Fehler! Verweisquelle konnte nicht gefunden werden., the evolution of burner power, roof temperature, flue gas temperature, and molten bath temperature during a representative melting cycle highlights the different phases of the process. The figure also illustrates the delayed appearance of the bath temperature signal, which corresponds to the insertion of the thermocouple into the molten metal once sufficient liquid aluminum is present.

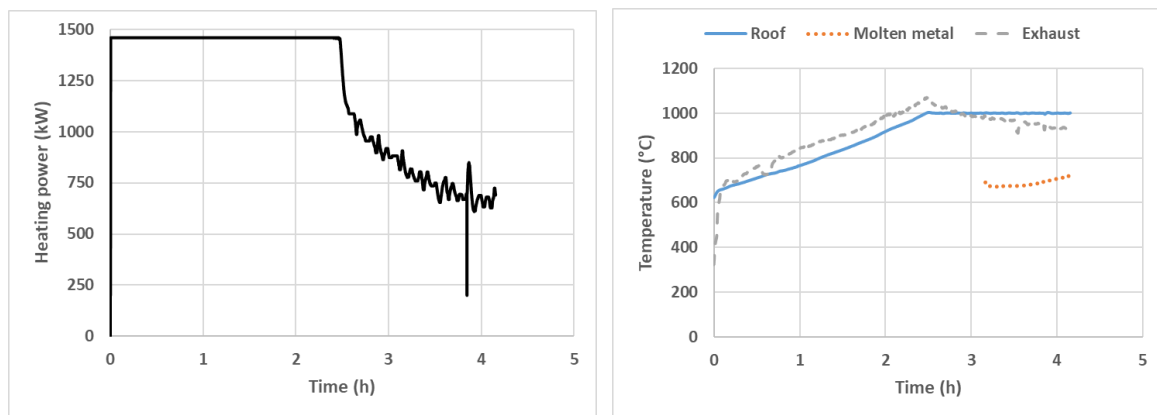


Figure 43: Evolution of heating power (left) and temperature profiles of the furnace roof, flue gases, and molten aluminum bath (right) during a complete melting cycle using pure hydrogen combustion

The temperature profiles highlight two distinct regimes. During the high-power phase, flue gas temperatures exceed roof temperatures due to the strong heat release and high gas flow rates. When the burner power is reduced, an inversion is observed, with lower flue gas temperatures compared to the roof temperature. This behavior is attributed to increased air ingress into the furnace at lower flow rates. Although a slight overpressure (typically around 9–11 Pa) is maintained in the furnace, reduced flue gas flow may lead to less effective sealing conditions and increased air infiltration.

The experimental dataset encompasses approximately one hundred industrial cycles performed between 2024 and 2025 under different operating conditions. Two main operating regimes were investigated: low-power operation (around 1.4 MW, single burner) and higher-power operation (up to 1.8–2.0 MW, two burners). The majority of the tests were performed with natural gas, complemented by a limited number of trials using hydrogen and hydrogen–natural gas blends.

Due to the fully industrial nature of the trials, a significant variability is observed from one cycle to another. This variability is mainly related to operational factors such as charge characteristics (mass, geometry, and distribution in the furnace) and operator practices, which are only partially controlled. As a result, the analysis presented in the following sections focuses on identifying robust trends rather than small variations between test conditions.

4.3 Thermal performance

The thermal performance of the furnace is assessed using two key performance indicators (KPIs): the Surface Melt Rate per Hour (SMRH) and the Specific Energy Consumption (SEC). The SMRH, expressed in $\text{kg}_{\text{Al}}/\text{h}/\text{m}^2$, characterizes the melting productivity normalized by the bath surface area, while the SEC, expressed in $\text{kWh}_{\text{LHV}}/\text{t}_{\text{Al}}$, quantifies the energy required to melt one ton of aluminum based on the lower heating value of the fuel. These two indicators provide complementary information, respectively reflecting the intensity of heat transfer to the metal and the overall energy efficiency of the process.

4.3.1 Surface melt rate

The surface melt rate is first analyzed for two distinct operating regimes: low-power and high-power conditions. As shown in Fehler! Verweisquelle konnte nicht gefunden werden., the distributions of SMRH are presented for both regimes, together with the mean value for natural gas operation and the associated 95% confidence interval, which provides a reference for assessing statistical dispersion.

Under low-power conditions, 28 industrial cycles were analyzed, including two trials performed with hydrogen. Under high-power conditions, the dataset includes 42 usable cycles, including two hydrogen trials and two trials with fuel blends. The operating conditions differ significantly between the two regimes, with target roof temperatures of approximately 1000 °C and 1050 °C, and burner powers ranging from 1200–1500 kW and 1800–2000 kW for low- and high-power operation, respectively.

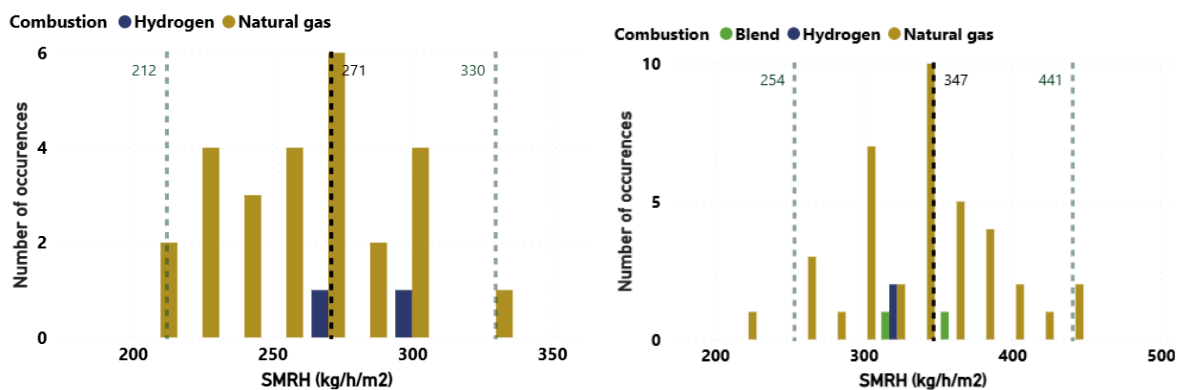


Figure 44: Distribution of surface melt rate per hour (SMRH) under low-power (left) and high-power (right) operating conditions

As illustrated in Fehler! Verweisquelle konnte nicht gefunden werden., a wide distribution of SMRH values is observed for both operating regimes. This variability is characteristic of industrial remelting furnaces and can be attributed to several operational factors, including variations in the total aluminum charge, the nature and geometry of the scrap, and the spatial distribution of the material inside the furnace. These parameters directly influence the effective heat transfer area and the exposure of the solid charge to radiative heat flux, which are key drivers of the melting kinetics.

A clear and statistically significant increase in melt rate is observed when increasing the burner power. The SMRH increases from typical values around 270 kg_{Al}/h/m² under low-power conditions to approximately 350 kg_{Al}/h/m² under high-power operation. This represents an increase on the order of 25–30%, which is consistent with the higher heat flux delivered to the metal at increased thermal input. In reverberatory furnaces, heat transfer is dominated by radiation from hot refractory surfaces and combustion products and increasing the burner power leads to higher wall temperatures and radiative fluxes, thereby accelerating the melting process.

In contrast, no visible effect of hydrogen or hydrogen–natural gas blends can be identified within the observed variability. This result is consistent with theoretical expectations. Under oxyfuel conditions, the main heat transfer mechanisms are not significantly altered by the substitution of natural gas with hydrogen. Although hydrogen combustion leads to a higher concentration of water vapor in the flue gas and the absence of CO₂, the overall emissivity of the gas phase remains of the same order of magnitude. As a result, the radiative heat transfer to the metal surface is not significantly modified.

4.3.2 Specific energy consumption

The specific energy consumption is evaluated using the full dataset, which includes 99 industrial cycles performed under various operating conditions, including three blend trials and four hydrogen trials. The corresponding distribution is presented in Fehler! Verweisquelle konnte nicht gefunden werden..

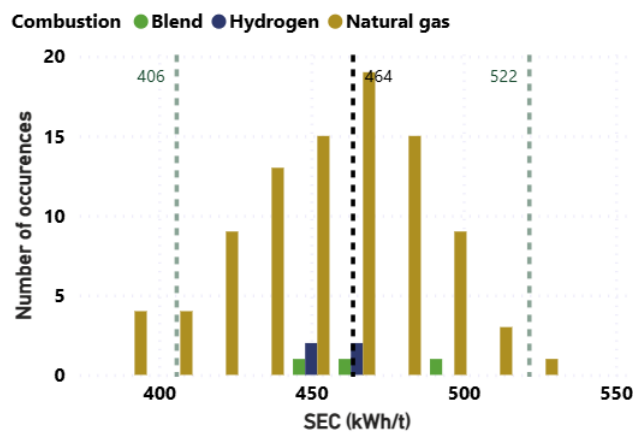


Figure 45: Distribution of specific energy consumption (SEC) for the full experimental dataset

As shown in Fehler! Verweisquelle konnte nicht gefunden werden., the SEC exhibits significant variability, with average values around 460 kWh_{LHV}/t_{Al}. This level of dispersion is typical of industrial operations and reflects the combined influence of several factors affecting the overall energy balance.

Variations in SEC can be attributed to differences in charge characteristics, such as total mass, initial temperature, and oxidation state, as well as to operational parameters including door opening durations, heat losses, and deviations from nominal operating conditions. In addition, the spatial arrangement of the charge within the furnace plays a key role in determining how effectively radiative heat is absorbed by the material, which directly impacts both melting time and energy consumption.

Despite the differences in combustion properties between natural gas and hydrogen, no clear or consistent impact of hydrogen on SEC is observed within the experimental uncertainty. This result can be explained by considering the global energy balance of the furnace. While hydrogen combustion produces a higher flue gas volume and a larger fraction of water vapor, these effects are compensated by differences in thermophysical properties, resulting in similar overall heat transfer conditions and comparable convective losses through the exhaust.

Overall, the results indicate that the thermal performance of the furnace is primarily governed by operating conditions, particularly burner power and charge-related factors, while the effect of fuel composition remains of second order. Under the investigated oxyfuel conditions, the substitution of natural gas with hydrogen does not lead to a measurable change in either melt rate or specific energy consumption at the industrial scale.

4.4 Dross formation

Dross formation is evaluated through the gross melting dross rate at the end of the melting phase. This indicator is defined as the mass of dross removed after skimming, normalized by the total mass of aluminum charged into the furnace. It therefore represents a global estimate of oxidation losses, without correction for the residual metallic aluminum content in the dross.

The analysis is based on the same dataset as for specific energy consumption, including 99 industrial cycles performed under various operating conditions and fuel compositions. The statistical distribution of the melting dross rate is presented in the next figure:

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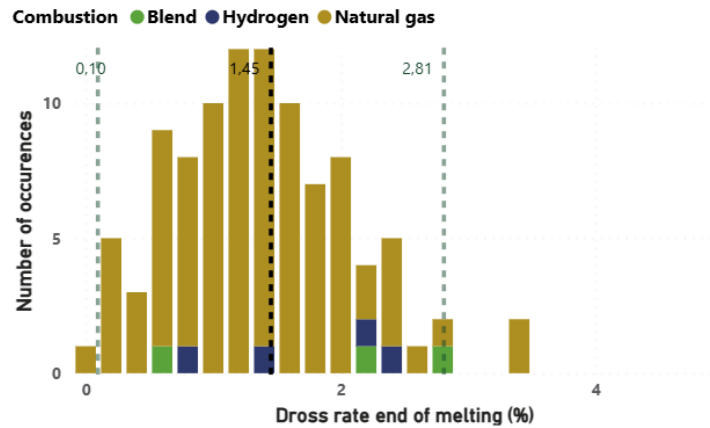


Figure 46: Distribution of melting dross rate for the full experimental dataset

As shown in Fehler! Verweisquelle konnte nicht gefunden werden., the dross rate exhibits a very large dispersion, with values typically centred around 1.5 wt%, but ranging over a factor of up to two between individual cycles. This variability is significantly higher than that observed for thermal performance indicators such as SMRH or SEC, which highlights the limited level of control associated with this KPI under industrial conditions.

Several factors contribute to this dispersion. The measurement itself involves manual skimming operations, which introduce an intrinsic uncertainty related to operator practices and to the difficulty of consistently separating oxide layers from residual molten aluminum. In addition, dross formation is strongly influenced by process conditions, including charge characteristics, loading practices, and the interaction between the flame and the metal surface.

In industrial reverberatory furnaces, dross formation is primarily driven by oxidation reactions occurring at the surface of the molten bath and exposed solid aluminum. These reactions are highly sensitive to local conditions such as temperature, oxygen availability, and surface agitation. Direct interaction between the flame and the metal, combined with mechanical disruption of oxide layers during melting, can promote oxidation and contribute to dross generation.

Within this context, the influence of fuel composition remains difficult to isolate. Hydrogen combustion leads to higher water vapor concentrations in the furnace atmosphere, which may influence oxidation mechanisms. However, this effect interacts with multiple other factors related to furnace operation and flow conditions. As a result, any potential impact of hydrogen on dross formation remains masked by the overall variability of the process.

Consistent with these observations, no clear or statistically robust effect of hydrogen on the melting dross rate can be identified in the industrial dataset. The variations observed between cycles are dominated by operational factors rather than by fuel composition. This indicates that, under the investigated conditions, dross formation is primarily governed by furnace operation and practices, such as heat distribution, burner positioning, and charging conditions, rather than by the nature of the fuel alone.

4.5 Impact on metal quality

The impact of fuel composition on metal quality was assessed through several complementary indicators, including inclusion cleanliness, dissolved hydrogen content, and microstructural characteristics of the cast products. The analysis was conducted on industrial samples produced during the experimental campaigns, mainly for 3xxx and 7xxx series alloys.

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4.5.1 Inclusion cleanliness

Inclusion cleanliness was evaluated using PoDFA and Batscan measurements. The PoDFA inclusion index, expressed as total inclusion area, remains in the range of 0.005 to 0.05 mm²/kg for all tested conditions. These values are consistent with typical industrial references obtained under natural gas operation.

Batscan measurements confirm these observations, with no abnormal peaks or deviations detected across the different fuel compositions. The results indicate that inclusion levels remain stable and are not affected by the nature of the fuel under the conditions investigated.

4.5.2 Dissolved hydrogen content

The dissolved hydrogen content in the molten aluminum was measured at the furnace outlet and after downstream treatment. At the furnace outlet, hydrogen levels are typically in the range of 0.20 to 0.30 mL H₂ per 100 g of aluminum under both natural gas and hydrogen operation.

After standard degassing and filtration treatments, including IRMA and Alpur processes, the hydrogen content is consistently reduced below 0.10 mL per 100 g of aluminum. No increase in dissolved hydrogen is observed when operating with hydrogen as fuel, indicating that the higher water vapor concentration in the furnace atmosphere does not lead to increased hydrogen pickup in the molten metal under the investigated conditions.

4.5.3 Microstructure and casting quality

Microstructural analysis of the cast products shows no measurable modification associated with the fuel composition. Grain size remains in the range of 110 to 150 µm depending on the alloy. Similarly, no changes are observed in macro segregation profiles or in the thickness of the solidified shell, which typically ranges from 9 to 15 mm.

These results indicate that the thermal and metallurgical conditions during melting and casting remain stable regardless of the fuel used.

4.5.4 Synthesis

Across all investigated indicators, no impact of hydrogen on metal quality is observed. Inclusion cleanliness, dissolved hydrogen content, and microstructural characteristics remain consistent with values obtained under natural gas operation.

These results confirm that, under industrial oxyfuel conditions and with standard downstream treatment processes, the substitution of natural gas with hydrogen does not lead to any measurable degradation of metal quality.

4.6 Nox emissions

NO_x emissions were monitored during experimental campaigns using gas analyzers installed on the furnace exhaust line. The measurement system combines two complementary instruments. NO_x and oxygen concentrations are measured using an extractive analyzer (NT 1, Lamtec), while the full flue gas composition, including H₂O, CO₂, and CO, is obtained using an MCS300P system. All measurements are performed on a wet basis using heated sampling lines to avoid condensation.

The evolution of furnace temperature, heating power, and flue gas composition during a representative melting cycle is presented in the next figure. During the high-power phase, NO_x emissions remain relatively stable. As the burner power is reduced, an increase in NO_x concentration is observed. This behavior is associated with increased air ingress into the furnace at lower flow rates, which leads to higher oxygen concentrations in the flue gas and increased availability of nitrogen in the reaction zone.

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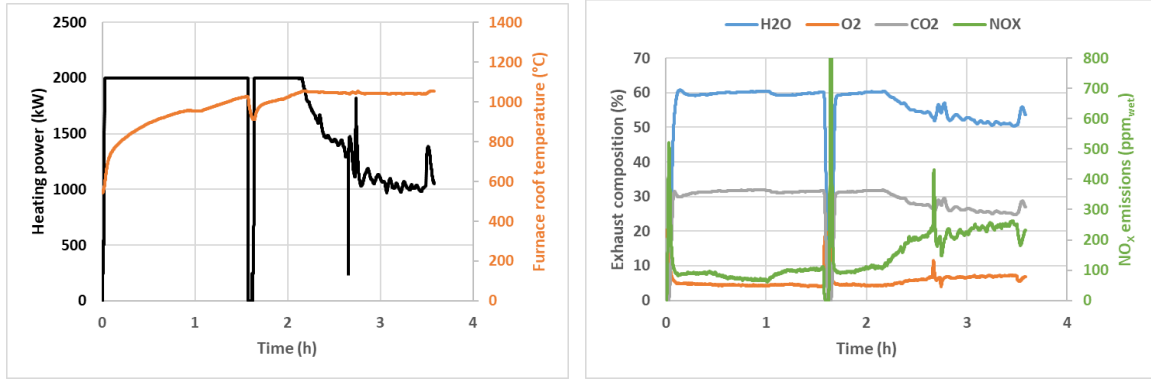


Figure 47: Heating power and furnace temperature during a high-power natural-gas cycle (on the left) and flue-gas composition (O₂, NO_x, CO₂, H₂O) during the melting cycle (on the right)

To assess the influence of fuel composition under controlled conditions, additional short-duration tests were performed. These tests consist of operating the furnace empty for approximately ten minutes, allowing the flue gas composition to stabilize. This methodology provides representative NO_x levels for steady-state high-power conditions, while minimizing transient effects associated with the melting cycle.

The tests were conducted at 1.4 MW and 1.8 MW, using two burners with an equal split of thermal power. A slight excess of oxygen was maintained in all cases, corresponding to approximately 2% oxygen in the flue gas. In addition, a controlled overpressure of about 11 Pa was applied to limit air ingress and ensure stable combustion conditions. Different fuel compositions were investigated, ranging from pure natural gas to hydrogen-rich mixtures.

To enable comparison between fuel compositions, NO_x concentrations measured in ppm on a wet basis were converted into specific emissions expressed in grams of NO_x per ton of aluminum. The conversion follows the methodology proposed by Schmitz et al., assuming a constant specific energy consumption of 460 kWh_{LHV} per ton of aluminum.

The theoretical flue gas volume is calculated as:

$$V_{flue} = SEC \times (r_{H_2} \cdot V_{spe,H_2} + (1 - r_{H_2}) \cdot V_{spe,NG})$$

where

$$V_{spe,NG} = 0.308 \text{ Nm}^3 / \text{kWh}_{LHV} \text{ and}$$

$$V_{spe,H_2} = 0.345 \text{ Nm}^3 / \text{kWh}_{LHV},$$

and r_{H_2} is the hydrogen energy fraction in the fuel mixture.

The NO_x emissions are then calculated as:

$$NO_x \left[\frac{gNO_x}{tAl} \right] = NO_x [\text{ppm}_{wet}] \times \frac{21\% - 2\%}{21\% - [O_2]_{wet}} \times \frac{M_{NO_x}}{22.4} \times V_{flue}$$

where M_{NO_x} is the molar mass expressed as NO₂, with $M_{NO_2} = 46 \text{ g/mol}$

This formulation accounts for the increase in flue gas volume associated with hydrogen combustion, which leads to higher mass emissions even when concentration levels remain comparable.

The results of this analysis are presented in the next figure. For hydrogen fractions up to approximately 50%, no significant increase in NO_x emissions is observed compared to natural gas operation. At higher hydrogen contents, an increase in NO_x emissions is detected, reaching values on the order of 50 g_{NO_x}/t_{Al} at around 90% hydrogen. A decrease is observed at 100% hydrogen, which is attributed to the reduced presence of nitrogen in the combustion environment.

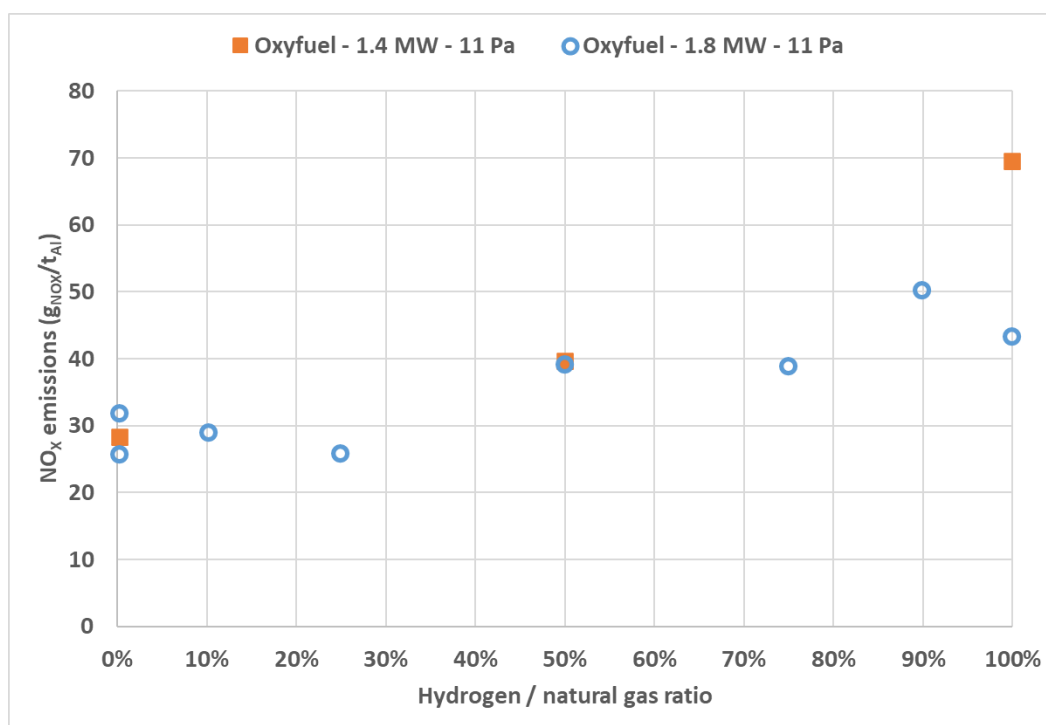


Figure 48: NO_x emissions (gNO_x/tAl) as a function of hydrogen content under controlled short-duration tests

These trends can be interpreted considering the mechanisms governing NO_x formation in oxyfuel furnaces. Although hydrogen combustion can lead to locally higher flame temperatures, which favours thermal NO_x formation, the availability of nitrogen remains the controlling parameter. In oxyfuel conditions, nitrogen originates mainly from air ingress into the furnace but can also be introduced through trace impurities in oxygen and fuel streams. As a result, NO_x emissions are highly sensitive to furnace tightness and gas purity.

This sensitivity is also reflected in the influence of operating conditions. Cases with lower furnace pressure tend to exhibit higher NO_x emissions, which is consistent with increased air infiltration and higher oxygen concentrations measured in the flue gas. This correlation highlights the dominant role of uncontrolled air ingress in supplying nitrogen to the reaction zone, thereby promoting NO_x formation.

Overall, the results indicate that NO_x emissions under oxyfuel conditions are primarily governed by nitrogen availability, which depends on furnace sealing, pressure control, and gas purity. The effect of hydrogen becomes noticeable only at high substitution rates, while for moderate hydrogen contents, NO_x emissions remain comparable to those obtained with natural gas.

4.7 Modelling approach and numerical simulations

The industrial demonstrator is a batch aluminum reverberatory furnace with a maximum melting capacity of 12 t, used for both remelting and holding prior to casting. The furnace has external dimensions of 4.5 m (depth) × 3.7 m (width) × 2.8 m (height) and a liquid-bath surface area of 10.4 m², and it is equipped with an ABB electromagnetic stirrer (EMS) to enhance bath homogeneity. The unit was originally equipped with a 2.4 MW cold-air burner and subsequently retrofitted for oxyfuel operation using two staged Linde LTOF (Low Temperature Oxy-Fuel) burners with a total installed power of 2 MW; the retrofit is intended to improve temperature uniformity and reduce NO_x through staged, semi-flameless combustion. The LTOF burner design injects around 30% through a central port and 70% of oxygen through peripheral lances to induce internal gas recirculation and a delay mixing, creating a semi-flameless regime that reduce the temperature rise, minimizing local hot spots and refractory stress.

The burner is designed for flexible operation with natural gas, hydrogen, or blends with a minimum contribution of 10% thermal power from each fuel, maintaining a constant molar oxygen-to-fuel ratio to

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ensure stable stoichiometry. The system incorporates UV flame detection cells for reliable flame monitoring under oxyfuel conditions.

4.7.1 Modelling methodology

The modelling of the reverberatory furnace is complex due to the transient heating and melting processes. Turbulent fluid dynamics and chemical kinetics have characteristic time scales on the order of 10^{-1} – 10^0 seconds and 10^{-3} – 10^{-2} seconds, respectively, whereas heat transfer in solids and, moreover, the melting cycle occur on time scales of hours. Therefore, high-fidelity models such as CFD are very costly and time consuming, limiting their use in supporting the design and evaluation of these types of processes. Low-fidelity models are an attractive alternative for the modelling of reverberatory furnaces. A simplified transient model of the industrial demonstrator is implemented in COMSOL Multiphysics (v5.5). This simplified model serves as a design tool and enables efficient comparison of combustion technologies and fuel mixtures, predicting melting performance in terms of specific energy consumption.

The simplified model is described in detail in [1]. The furnace is represented as a 3D domain including refractory layers (with thermodynamic properties) and a flat aluminum bath with temperature-dependent solid/liquid properties. Heat transfer in solids is solved by conduction, while the wall heat losses to the furnace surroundings are represented by a fixed natural heat-transfer coefficient and wall emissivity. Combustion is not spatially resolved; instead, the furnace atmosphere is represented by a zero-dimensional transient energy balance that converts burner power into an effective gas temperature and composition. Convective and radiative heat transfer between the gas, walls, and metal bath are imposed through engineering correlations using fixed heat-transfer coefficients and a grey-gas/grey-surface radiation model, with parameters estimated from the literature and calibrated against experiments. The heat transfer coefficient for the convective heat transfer from furnace gas atmosphere is fixed to $40 \text{ W/m}^2/\text{K}$. While the surface emissivity for radiation heat transfer is set to 0.8 for the internal and external wall faces and 0.55 for the aluminum. The effect of electromagnetic stirring is incorporated through an experimentally derived equivalent thermal conductivity for liquid aluminium. Finally, the effective metal surface area during melting is adjusted to account for the effect of the melting process (aluminium shape) on the heat flow [1]. The adjustment of the metal surface area is calibrated based on experimental data.

An example of the result of the calibration process is shown in the Figure 45. The simulated melting cycle is initialized from a steady-state empty furnace (walls at 600°C), when 12 tons of 20°C metal are charged and heated under specified burner powers until the roof reaches the target temperature, after which power is controlled (gradually reduced) to hold that roof temperature until the metal reaches 750°C .

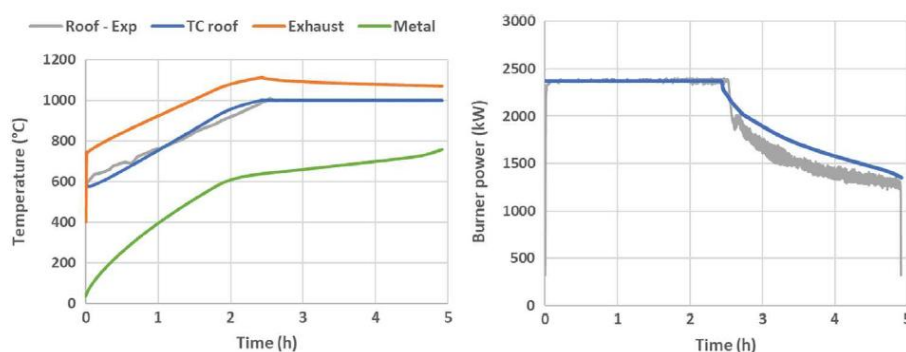


Figure 49: Calibration of the model on experimental data for cold-air combustion. Temperature profiles of roof, exhaust gas, and metal surface (left) and burner thermal power (right). Grey lines represent the experimental reference data

The figure displays the modelled performances for different combustion technologies (Air-NG, Air- H_2 , O_2 -NG, and O_2 - H_2) while maintaining a constant net maximum installed heating power. Compared to the experimental results with natural gas, the model demonstrates high predictive accuracy, as the results closely match the experimental data, although it exhibits a slight systematic discrepancy by overestimating the Specific Energy Consumption (SEC) by approximately 5%.

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Regarding the impact of the fuel, the model predicts that switching to hydrogen combustion reduces the SEC by 9% when cold air is used as the oxidizer, while having no significant impact when pure oxygen is used. Furthermore, consistent with the experimental observations, the model predicts that the Surface Melt Rate per Hour (SMRH) and, consequently, the overall melting time remain unchanged across all combustion technologies. This confirms that maintaining a constant net maximum heating power results in identical heating rates regardless of the fuel or oxidizer blend employed.

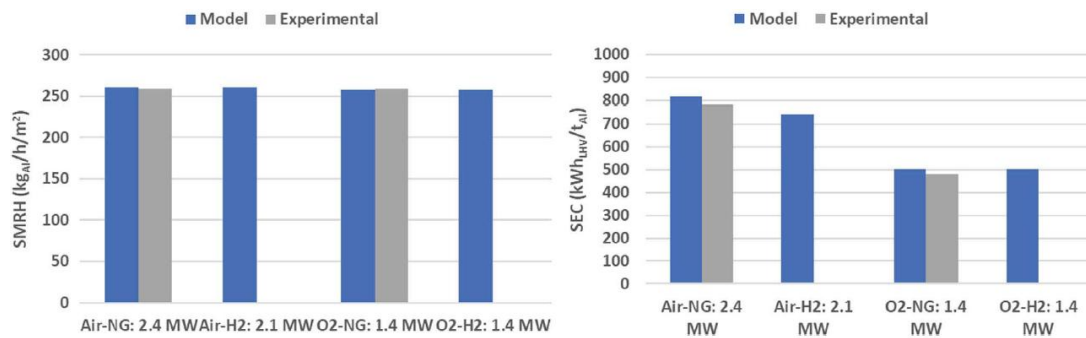


Figure 50: Results of the surface melt rate per hour (SMRH) and specific energy consumption (SEC) from experimental trials and the simplified model

4.8 CFD simulation

The simplified model demonstrates the ability to predict the performance of the transient heating process in aluminum melting furnaces in agreement with experimental data from an industrial reverberatory furnace demonstrator, accurately reproducing key performance indicators such as Specific Energy Consumption (SEC). It also provides valuable insights into the distribution of heat fluxes during the melting cycle and enables the evaluation of the effects of different combustion technologies and fuel mixtures. Although simplified, the model is a robust tool for supporting retrofit projects with significantly lower computational cost and run time than CFD simulations. Nevertheless, CFD simulations remain necessary, particularly to investigate aspects such as the effect of the burner design and location on the heat transfer, and flow patterns inside the furnace, as well as detailed chemistry and emissions.

CFD simulations can be used to provide inputs to the simplified model within a multi-fidelity framework, without the need to compute a fully transient CFD simulation of the entire melting process. This approach increases the predictive capability of the simplified model while reducing its dependence on experimental calibration. In the present case, CFD simulations of the industrial reverberatory furnace demonstrator are performed to assess some of the assumptions of the simplified model and to gain deeper insight into the reaction zone of the low temperature oxyfuel burner when operated with both natural gas and hydrogen fuels.

Steady-state RANS CFD simulations are performed at five representative time positions along the melting cycle, as illustrated in Figure 47. The thermal power and the temperatures of the walls and metal surface are used as boundary conditions for the CFD simulations. The five cases are distributed such that the two main

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phases—(i) transient heating with constant thermal power and (ii) constant-temperature melting with decreasing thermal power—are well represented.

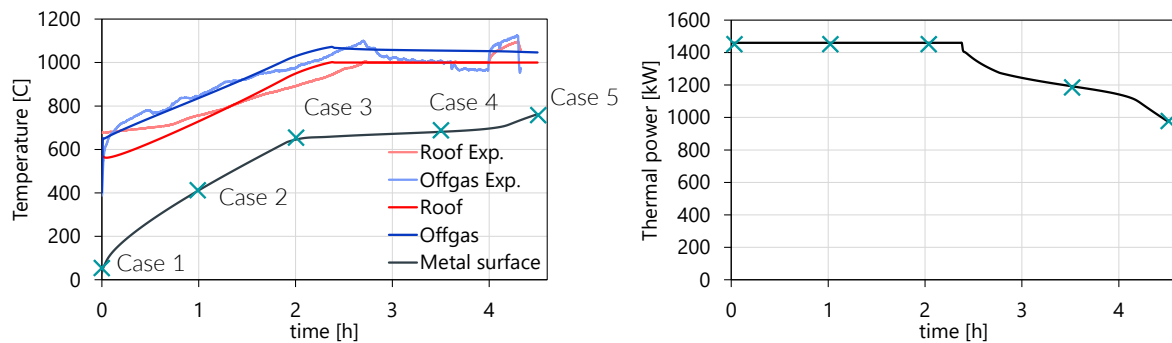


Figure 51: Reference cases for the CFD simulations along the melting cycle. The continue lines correspond to the data from the simplified model, while the broken lines correspond to experimental measurements for NG-Oxy for low-power (1.4MW)

The computational domain for the CFD simulations is illustrated in Figure 48. The low-power regime is considered, in which only one low-temperature oxyfuel burner is used. The initial thermal power is 1460 kW and then decreases following the melting cycle. The oxygen excess ratio (λ) is fixed at 1.11, corresponding to an equivalence ratio (ϕ) of 0.9, while the oxygen staging is set to 30%, meaning that 30% of the oxygen is injected through the primary central nozzle and the remaining 70% through the secondary high-speed lances.

As in the simplified model, the surface representing the molten aluminium is fixed during the whole melting cycle, ignoring the real geometry of the solid aluminium at the beginning of the cycle. This will be reflected on the results of the heat transfer and highlight the role of the effective metal surface area variable in the simplified model.

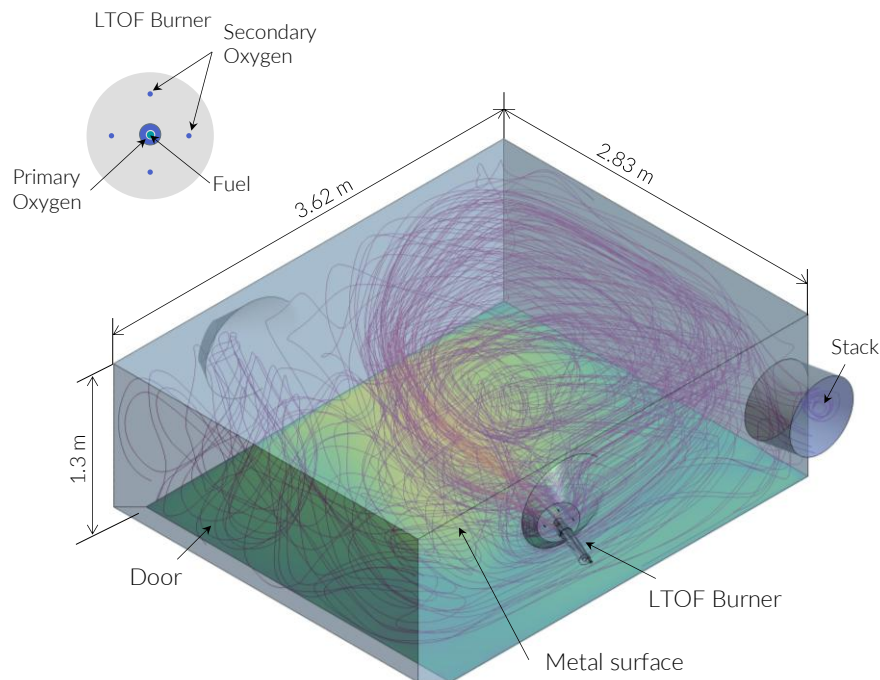


Figure 52: Computational domain of the industrial reverberatory furnace demonstrator with the low-temperature oxyfuel burner

The numerical simulations are performed on an unstructured computational mesh consisting of approximately 0.875 million polyhedral cells with a base size of 80 mm. To improve the resolution of injection, mixing, and combustion processes, additional progressive mesh refinements of 40, 20, 8, and 2 mm are

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applied in the burner and reaction zone region. A ten-layer prism mesh is applied at the wall boundaries, with a wall y -plus below 2.

The governing equations are solved assuming a compressible ideal-gas formulation using a double-precision, pressure-based solver implemented in ANSYS Fluent 2023 R1. Pressure-velocity coupling is handled with a pseudo-transient coupled scheme, while pressure interpolation is achieved using the PRESTO! method [2]. A second-order upwind discretization is adopted for the convective terms of all transport equations. Within the RANS framework, turbulence closure is achieved through the κ - ω SST (Shear Stress Transport) model [3], based on the Boussinesq approximation and combining κ - ω behaviour in near-wall regions with κ - ϵ behaviour in the free stream. Radiative heat transfer is accounted for using the Discrete Ordinates Model (DOM) [4] with a 4×4 angular discretization. Gas-phase radiative properties are evaluated using a weighted-sum-of-gray-gases (WSGG) model calibrated for oxyfuel combustion in Task 1.4 [5], while the emissivity of all internal walls is set to 0.6. The interaction between turbulence and chemical kinetics is described using the Eddy Dissipation Concept (EDC) model [6,7]. Molecular transport properties of both individual species and the mixture are calculated using kinetic gas theory and mixture-averaged formulations, and thermal diffusion (Soret effect) is included. Turbulent diffusion of heat and species is modelled using the gradient diffusion hypothesis, with turbulent Prandtl and Schmidt numbers set to 0.85 and 0.7, respectively.

Two sets of CFD simulations are performed: one for natural gas oxyfuel combustion and a second for hydrogen oxyfuel combustion. The DRM22 kinetic mechanism [8] is used for the natural gas oxyfuel case, while the C3MechLite [9] mechanism is employed for the hydrogen oxyfuel case.

4.8.1 CFD simulations Results

The results of the CFD simulations for natural gas oxyfuel combustion are analyzed first. The next figure shows the evolution of temperature and heat flows for the walls, off-gas, and metal surface along the melting cycle. Since the wall (roof) and metal surface temperatures from the simplified model are used as boundary conditions in the CFD simulations, they are not compared. In contrast, the simplified model assumes that the gas temperature is equal to the wall temperature, whereas the gas temperature is explicitly solved in the CFD simulations. The CFD results show that both the average gas temperature in the furnace and the off-gas temperature are in very close agreement with the wall temperature. The discrepancy observed at the beginning of the melting cycle, where the CFD predicts a higher gas temperature, is due to the misrepresentation of the actual surface area of the solid aluminum. This effect is accounted for in the simplified model through the effective metal surface area, which acts as a correction factor for the heat flow to the metal. This behaviour is more clearly observed when examining the heat flow to the metal in Figure 50. The CFD predicts a much lower heat flow to the metal compared to the simplified model; however, when the metal surface area adjustment is not applied (model w/o correction), the heat flow predicted by the simplified model agrees with the CFD results.

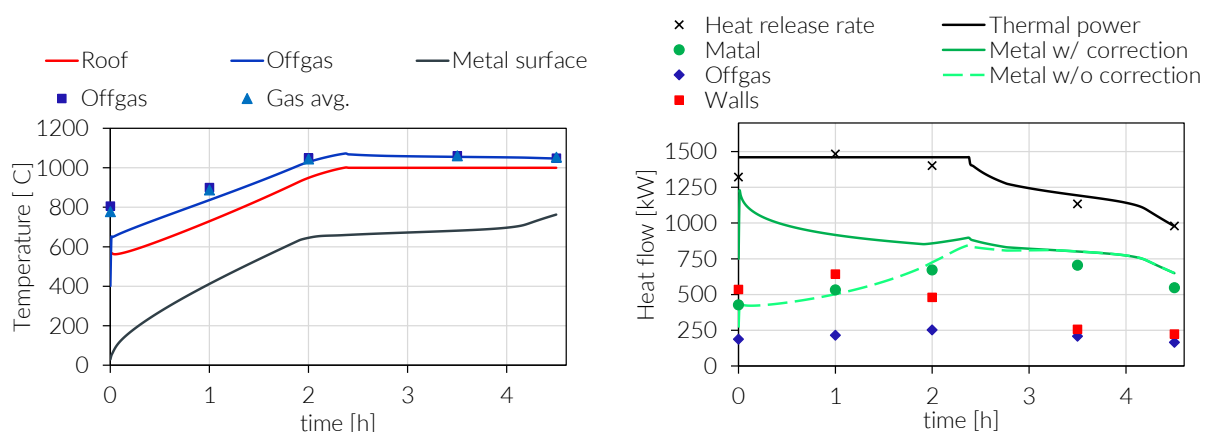


Figure 53: Temperature profiles of roof, exhaust gas, and metal surface (left) and burner heat flow distribution (right). Simplified model results (lines) compared to the CFD simulations (markets). NG-oxyfuel condition

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The adjustment of the effective metal surface area affects both convective and radiative heat transfer; therefore, both heat flows are overpredicted in the CFD at the beginning of the melting cycle compared with the simplified model, as shown in the next figure. Nevertheless, when comparing heat fluxes (heat flow per unit surface area), good agreement is observed between the CFD results and the simplified model.

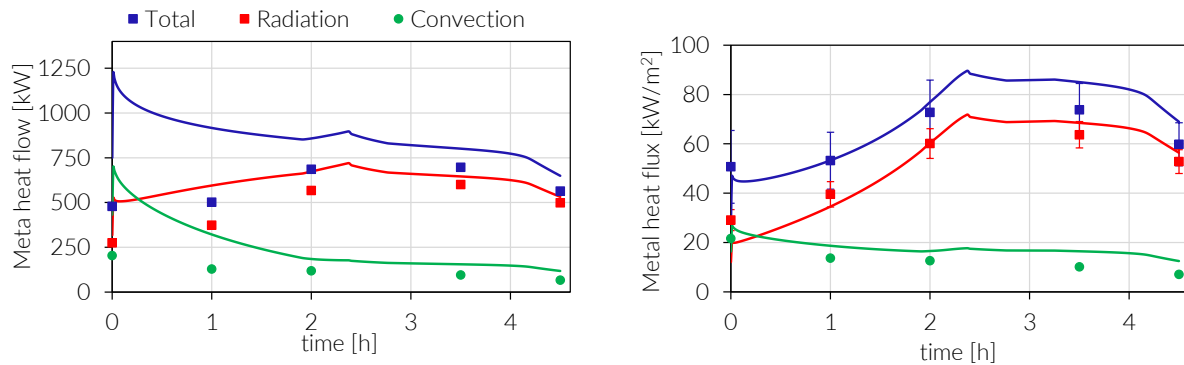


Figure 54: Heat flow (left) and heat flux (right) to the metal. Simplified model results (lines) compared to the CFD simulations (markets). NG-oxyfuel condition

The overall agreement in heat fluxes between the CFD and the simplified model confirms that these heat-transfer mechanisms are well represented in the simplified model. However, some differences are observed, such as an underprediction of the radiative heat flux at the beginning of the melting cycle and an overprediction of the convective heat flux throughout the cycle. These discrepancies arise from the values used for emissivity and convective heat-transfer coefficients in the simplified model, whereas these quantities are computed dynamically in the CFD simulations. A comparison between the model values and those computed by CFD is presented in the next figure. The gas emissivity is higher at the beginning of the melting cycle, when the gas temperature is lower, and decreases as the temperature rises, converging toward the value used in the simplified model. On the other hand, the convective heat-transfer coefficient used in the simplified model is approximately 33% higher than that computed in the CFD simulations. The convective heat-transfer coefficient to be used in the simplified model is more difficult to estimate a priori, as it depends on the fluid dynamics within the furnace. Nevertheless, its impact on the overall model performance is limited, since radiation dominates heat transfer in the furnace, with convection accounting for only about 20% of the total heat flow to the metal.

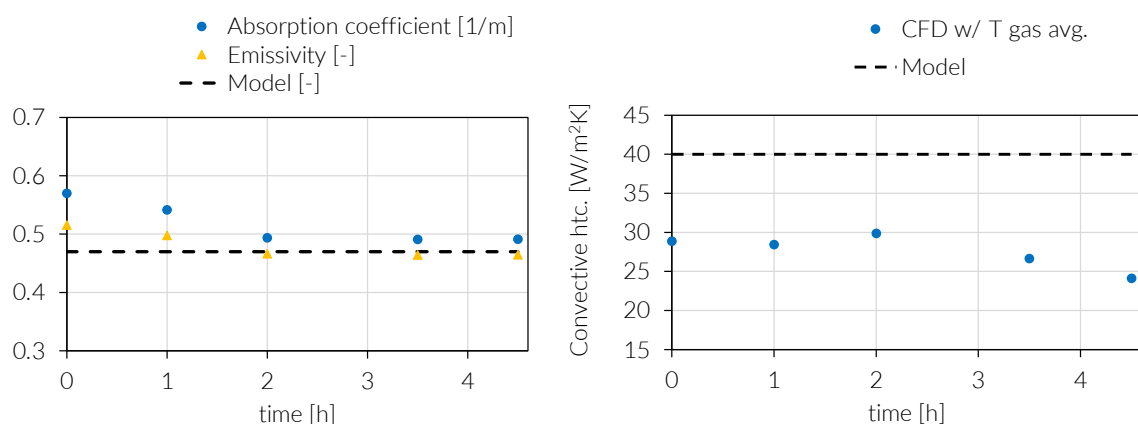


Figure 55: Gas emissivity (left) and convective heat transfer coefficient for the metal surface (right)

As already observed in the experimental tests and in the analysis with the simplified model, switching to hydrogen has a limited impact on the thermal performance of the industrial reverberatory furnace

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demonstrator. The contours of temperature and mole fractions of fuel species and OH radicals in the next figure show that, when hydrogen is used as fuel, the higher volumetric flow rate leads to deeper penetration of the fuel jet, while the higher reactivity results in a higher peak temperature and a more robust reaction zone. Nevertheless, the low-temperature oxyfuel burner develops an overall similar reaction zone regardless of the fuel composition. The highlights the flexibility of this burner technology and explain the low impact of hydrogen substitution on the furnace performance.

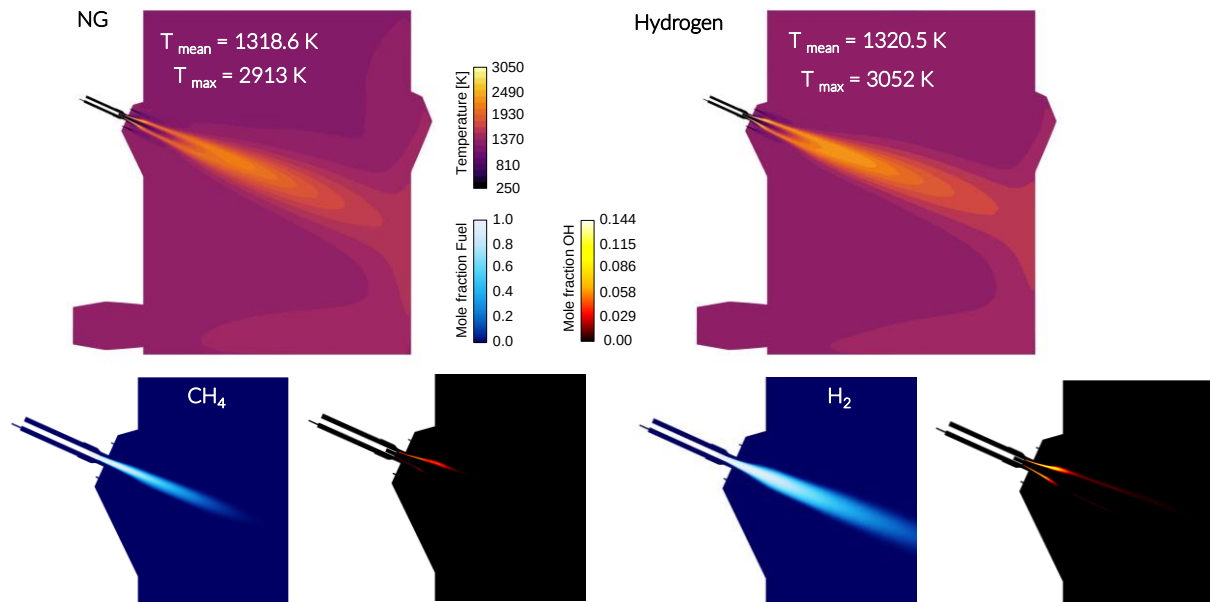


Figure 56: Contours of temperature, and mole fraction of fuel species and OH radical for natural gas – oxyfuel (left) and hydrogen – oxyfuel (right)

The oxygen injection scheme in the low-temperature oxyfuel burner leads to a semi-flameless reaction zone, in which a flame-like structure forms close to the burner mouth, observed as a high OH concentration region, followed by a more distributed reaction zone where radicals (such as OH) and temperature are diluted by the recirculation of lower-temperature flue gas. This semi-flameless operation combines some of the benefits of flameless combustion, such as homogeneous heat transfer and lower emissions, with the stability of conventional flame combustion, since fully flameless operation is not stable throughout the entire melting cycle due to the low wall temperatures at the beginning of the cycle.

The next figure compares the convective and radiative heat fluxes to the metal surface for natural gas and hydrogen as fuels. Both heat fluxes remain nearly constant when switching to hydrogen, with a slight increase of less than 3%. This behaviour results from the small difference in flame temperature between natural gas and hydrogen under oxyfuel combustion conditions. Moreover, both the convective heat-transfer coefficient and the gas emissivity change only marginally between the two fuels over the melting cycle. These results confirm that most of the assumptions done in the simplified model are valid for the various fuel mixtures.

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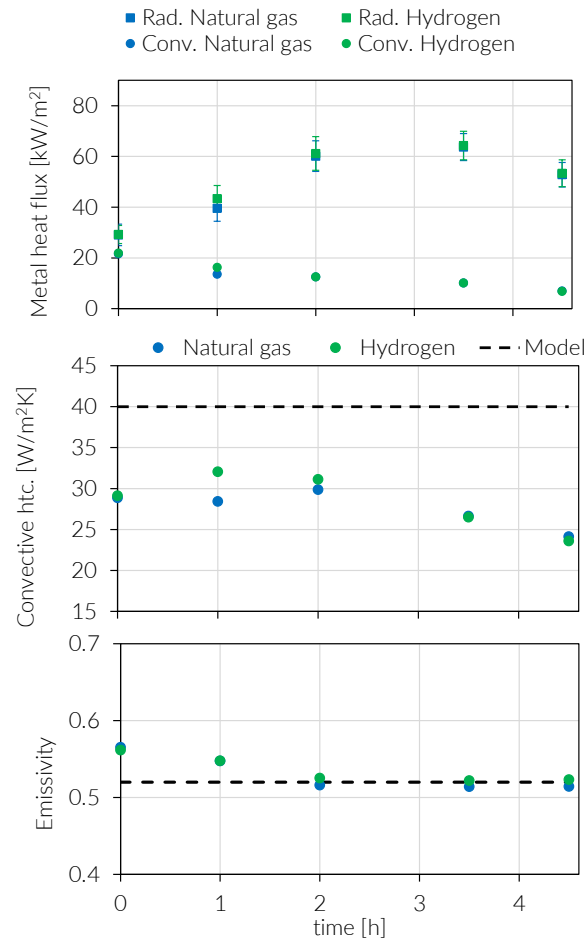


Figure 57: Comparison between natural gas and hydrogen on the heat flow to the metal (upper), convective heat transfer coefficient for the metal surface (middle) and gas emissivity (lower)

4.9 Limitations and scope of the study

The present study is based on industrial-scale experiments conducted under representative operating conditions. While this approach ensures a high level of relevance for real applications, it also introduces several limitations that must be considered when interpreting the results.

First, the experimental campaigns exhibit a significant level of variability between individual cycles. This variability is inherent to industrial operations and is mainly related to factors such as charge characteristics, loading practices, and operator interventions. These parameters are only partially controlled and can strongly influence key performance indicators, particularly those related to oxidation and dross formation.

Second, the number of tests performed with hydrogen and hydrogen-rich mixtures remains limited compared to the natural gas dataset. Although the available results provide consistent trends, the statistical robustness of conclusions related to hydrogen operation is therefore reduced. Additional long-term testing would be required to further consolidate these observations under a wider range of operating conditions.

Third, some measures rely on operational procedures that introduce additional uncertainty. This is particularly the case for the determination of the melting dross rate, which depends on manual skimming operations and may be affected by differences in practice between cycles. Similarly, the interpretation of NO_x emissions is influenced by factors such as air ingress and furnace pressure, which are difficult to control precisely under industrial conditions.

In addition, the experimental setup does not allow for a complete isolation of individual parameters. Several factors, including fuel composition, burner power, furnace pressure, and air infiltration, may vary

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simultaneously and interact with each other. As a result, the observed trends must be interpreted as global industrial responses rather than strictly controlled parametric dependencies.

Finally, the analysis focuses on short- to medium-term experimental campaigns. Potential long-term effects, such as the impact of hydrogen on refractory materials or gradual process drifts, are not addressed in the present study and require dedicated investigations.

Despite these limitations, the results provide a consistent and representative overview of the behaviour of an industrial oxyfuel aluminum melting furnace under hydrogen operation and allow robust conclusions to be drawn regarding the main process trends.

4.10 Conclusions

- This report presents the results obtained from industrial-scale experimental campaigns carried out on the C-TEC aluminum remelting furnace demonstrator within the HyInHeat project. The study assesses the impact of hydrogen use in oxyfuel combustion on furnace operation, thermal performance, metal quality, dross formation, and NO_x emissions.
- The analysis of thermal performance shows that the main process indicators, namely surface melt rate and specific energy consumption, are primarily governed by operating conditions such as burner power and charge characteristics. A clear increase in melt rate is observed with increasing thermal input, while the specific energy consumption remains within the typical range of industrial operations. No measurable impact of hydrogen on these indicators is identified within the experimental variability, indicating that substituting natural gas with hydrogen does not significantly affect the overall thermal performance of the furnace under the investigated conditions.
- Dross formation is found to exhibit a high level of variability, with values strongly influenced by operational factors and measurement practices. The results confirm that this KPI remains difficult to control at the industrial scale, and no statistically robust effect of hydrogen on the dross rate can be identified. The observed variations are dominated by process-related parameters rather than by fuel composition.
- The assessment of metal quality shows no detectable impact of hydrogen use on inclusion cleanliness, dissolved hydrogen content, or microstructural characteristics. The measured values remain consistent with those obtained under natural gas operation, demonstrating that the introduction of hydrogen does not lead to any degradation of the metallurgical quality of the aluminum under standard industrial conditions.
- The analysis of NO_x emissions highlights the dominant role of nitrogen availability and furnace operating conditions. Air ingress, furnace pressure, and gas purity are identified as key drivers of NO_x formation. For moderate hydrogen fractions, emissions remain comparable to those observed with natural gas. An increase in NO_x emissions is observed only at high hydrogen contents, while the overall levels remain strongly dependent on process conditions.
- Overall, the results demonstrate that hydrogen can be integrated into industrial oxyfuel aluminum remelting furnaces without significant impact on thermal performance or metal quality. The main process sensitivities remain associated with operational parameters rather than fuel composition. These findings support the technical feasibility of hydrogen use in such applications, while highlighting the importance of process control, particularly with respect to air ingress and furnace operating conditions.
- Based on the CFD evaluation and comparison with the simplified model, the results demonstrate that the low-fidelity modelling approach provides reliable predictions of furnace thermal performance while requiring only a fraction of the computational cost of full CFD simulations. The CFD results validated the main heat-transfer assumptions adopted in the simplified model and identified areas where model parameters, such as emissivity and convective heat-transfer coefficients, can be refined. This highlights the potential of a multi-fidelity framework in which a

limited number of carefully selected and relatively inexpensive CFD simulations are used to improve model assumptions and calibration, while the simplified model is employed to perform rapid evaluations of different operating conditions, combustion technologies, and fuel mixtures. Furthermore, both approaches confirmed that replacing natural gas with hydrogen in the low-temperature oxyfuel burner has only a minor impact on furnace thermal performance, demonstrating the flexibility of the burner design. Overall, the combined methodology provides an effective and computationally efficient tool for supporting furnace design, optimization, and retrofit projects.

4.11 References

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5 Reverberatory holding furnace and pusher furnace studies

5.1 Introduction

As part of the deliverable work, two studies are planned to evaluate the theoretical performance of two industrial size furnaces (a 60 reverberatory holding furnace and a 400-ton pusher furnace for aluminium slabs). The theoretical results of the studies are obtained based on the performance shown by other retrofitted furnaces on their tests, using their results as a guideline for the theoretical results that these industrial scale furnaces would obtain.

The following targets are set for these studies:

- Design, analyze and document the needed modifications of the furnaces for a successful retrofit, including burner selection, modifications of the lining, fuel supply, etc.
- Analyze the thermal performance of the furnaces based on the results obtained on the other demonstrators of WP5.
- Analyze the off-gas emissions that would be obtained
- Evaluate the CFD of the pusher furnace radiant tube and burner system

5.2 Metlen reverberatory furnace burner retrofit

5.2.1 Burner power selection

For the Metlen case, Bloom 1020-0200-80 burners are currently installed in the furnace. This type of burner is a baffled burner that recirculates exhaust gases into the combustion gases to limit the peak flame temperature and thus achieving reducing NO_x.

Due to the burner design, that mixes the fuel and air at the exit on the hot side of the baffle, flashback is minimized and allows application with several gases, such as hydrogen.

In case of a combustion replacement to go to higher efficiency the alternative would be going with oxy-fuel burners for hydrogen, as those would provide a be more efficient combustion system, removing the nitrogen and adding only oxygen removes a big part of the hot exhaust gases going out of the furnace that cause a loss of energy that is not used. Just by reducing the exhaust gases, the fuel efficiency is increased.

For selecting the needed burner power in the case of oxyfuel, we must consider the available heat when using 21%O₂ (with air) and 100%O₂ in the case of oxyfuel combustion. Assuming that the maximum furnace temperature will be around 1.000°C, we can consider that the available heat

5.2.2 Burner flame length

When comparing the flame length of the new oxyfuel burner we must consider the actual flame length that the current burner has, taking into consideration that a 1 MW oxyfuel burner will have an estimated length of 2.900mm.



Figure 58: Flame length of an oxyfuel burner

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Overall, the impact of the burners on the furnace will be approximately the same for a holder furnace. In the case of melting, the oxyfuel presents an improvement due to its higher convection thanks to the higher fumes speed, close to 100 m/s.

The flame length of the burner will depend on several factors such as burner design, applied power, and fuel used.

5.2.3 Burner quantity

In this case the best option is to place 3 burners as with the current configuration, due to the placement of the fumes exit near one of the furnace sides, a placement of a burner there could affect the flame as the fumes from all around the furnace would be directed to that area, and the flame itself could be sucked partially into the fumes, so the best option is to keep the 3 current burners in the same distribution.

5.2.4 Burner location

Burner location will remain the same for the reasons explained both with Air-hydrogen combustion and with Oxygen-Hydrogen combustion, as the position of the burners is optimal in this case.

5.3 Metlen Hydrogen gas supply

Based on the calculations done in WP3 and on deliverable D3.1 for the operating conditions of the demonstrators, the needed capacity for hydrogen is calculated and validated.

For the hydrogen gas supply, the maximum needed amount changes significantly when using air hydrogen burners or oxyfuel burners, with the following maximum needed:

- Air-Hydrogen burner: 1950 Nm³/h of hydrogen.
- Oxyfuel Hydrogen burner: 1060 Nm³/h of hydrogen.

For these consumptions and considering the possibility that the furnace may need to work at full power for heating the aluminium inside before casting or melt quickly pure aluminium or needed alloys, the most conservative assumption is to consider that the full capacity will be needed.

With that capacity in mind, the current trailers delivering Hydrogen can carry approximately 3000 Nm³ or 4000 Nm³ of Hydrogen so again, in a worst-case scenario that would mean the need to switch the trailers with this frequency:

- Air-Hydrogen burner: Every 2 to 3 hours.
- Oxyfuel Hydrogen burner: Every 3 to 4 hours.

That would impose the need to use a double trailer set-up for the supply of hydrogen, a system similar to the presented on the following image that has been provided in collaboration with the partners from Nippon gases.

This kind of station is needed for being able to work with 2 trailers at once, thus ensuring a continuous operation of trailers. The input pressure is about 200 bar, as that is the supply pressure of the hydrogen bottles, and needs to be reduced by a two-step reduction down to a more manageable pressure of 4 bars at the entry to the factory. Also, the system has a purging device consisting of nitrogen gas to clean all the pipes for safety ensuring a complete cleaning before restarting the system.

5.4 Metlen combustion P&ID

5.4.1 Natural gas – P&ID

The P&ID of the actual Metlen furnace burnerst has the following working principles for air and gas combustion with the current baffle burners:

- Flow measurement on both air and gas
- Gas safety system according to UNE-EN ISO 13577
- Main burner and pilot burner.
- One combustion fan for each burner.
- Rotary joint for connecting the main gas train and the rest of the circuit.
- Ultraviolet flame detection.

5.4.2 Air – Hydrogen – P&ID

Switching to hydrogen would imply modifying several elements that reflects the needed changes or modifications in red. In this case both the flow of hydrogen and air are reduced.

This study assumes can work with 100%hydrogen, should this not be the case, an equivalent direct fire burner should be installed of a similar power. The burner 1020 series has already been tested in Bloom laboratories with varying percentages but not up to 100% on this design, and that is something yet to be tested.

The main elements that change are the following when going with the air-hydrogen combustion:

- Hydrogen flow of 1950 Nm³/h instead of 565 Nm³/h of natural gas.
- Air flow of 1550 Nm³/h per burner instead of 2070 Nm³/h.
- A frequency inverter is recommended to be used due to the air flow change, as it will improve consumption and fan adequation for the lesser air needed.
- A safety electro valve to be able to evacuate hydrogen from the gas train is recommended to be installed, as this would allow for the evacuation of the not used gas and reduced the potential risk of leaks from the system.
- The already exiting ultraviolet flame detector is needed for the hydrogen flame detection.
- A pressure switch near the burner for detection hydrogen pressure, in case of the breakage of the flexible connection the supply of hydrogen into the corresponding line can be shut-off.

When considering the existing pipes that are used for natural gas, some of them exceed the recommendation from D3.1 that sets the recommended speed as 60 m/s for Hydrogen. For natural gas, that has also a recommended speed of 20 m/s maximum to avoid the degradation of the pipe and avoiding excessive pressure loses, the last part of DN50 seems too small.

In the case of conserving the piping for Hydrogen, there are two ducts where the recommended speed of 60 m/s is exceeded, after reducing the line pressure and near the burner.

HYDROGEN						
Piping			Flow speed			
DN	m	m2	m/s	m/s	m/s	m/s
65	0,065	0,00331831	35,40			
100	0,1	0,00785398	69,88			
65	0,065	0,00331831			55,13	
50	0,05	0,0019635				93,17
Gas conditions						
		Normal	High pres.	Low pres.	Burner 1	Burner 2
Pressure	mbar	1013	5013	1073	1073	1073
Flow	Nm ³ /h	1950	422,9	1975,8	658,6	658,6
Flow	Nm ³ /s	0,542	0,117	0,549	0,183	0,183

NATURAL GAS						
Piping			Flow speed			
DN	m	m2	m/s	m/s	m/s	m/s
65	0,065	0,00331831	10,26			
100	0,1	0,00785398		20,25		
65	0,065	0,00331831			15,97	
50	0,05	0,0019635				27,00
Gas conditions						
		Normal	High pres.	Low pres.	Burner 1	Burner 2
Pressure	mbar	1013	5013	1073	1073	1073
Flow	Nm ³ /h	565	122,5	572,5	190,8	190,8
Flow	Nm ³ /s	0,157	0,034	0,159	0,053	0,053

Figure 59: Metlen furnace gas trains for Hydrogen and natural gas

Thus, in case of a hydrogen retrofit it is recommended to change those ducts for bigger diameters if the budget allows for the reasons explained before. Increasing the size of the indicated ducts would reduce the speed as indicated below.

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HYDROGEN						
Piping			Flow speed			
DN	m	m2	m/s	m/s	m/s	m/s
65	0,065	0,00331831	35,40			
125	0,125	0,01227185		44,72		
65	0,065	0,00331831			55,13	
65	0,065	0,00331831				55,13
Gas conditions						
		Normal	High pres.	Low pres.	Burner 1	Burner 2
Pressure	mbar	1013	5013	1073	1073	1073
Flow	Nm3/h	1950	422,9	1975,8	658,6	658,6
Flow	Nm3/s	0,542	0,117	0,549	0,183	0,183

Figure 60: Metlen furnace recommended ducts for Hydrogen

5.4.3 Oxygen – Hydrogen – P&ID

Finally as the last options, the possibility to change the burner to Oxyfuel would increase the efficiency of the burner and reduce the exhaust gases, which in this case would be an advantage.

The main comments and conclusion from the P&ID are as follows:

- The main hydrogen burner operates with an ultraviolet cell for flame detection.
- Natural gas line is also included so the possibility to mix fuels from 0% to 100% is also possible.
- The pilot burner works with natural gas.
- Flow measurement is available for Oxygen, natural gas and hydrogen.
- Valve probing between the main natural gas and hydrogen electrovalves tests for potential leaks and evacuates the gas.

5.5 Metlen furnace modification

5.5.1 Lining modification

The lining needs to be modified around the burner block with a castable designed to be near burner blocks, as the current burner has a hole in the furnace of approx.. 406mm whereas the oxyfuel burner has an approximate block diameter of 120mm that can be installed along with its own refractory block. In any case it would be needed to modify the refractory and the steelwork for support of the burner.

5.5.2 Furnace steelwork modification

As explained in the refractory section, the steelwork needs to be modified for installing the new oxyfuel burner as the supports are designed for the bigger cold air burner. Following an example of a smaller oxyfuel burner supported.

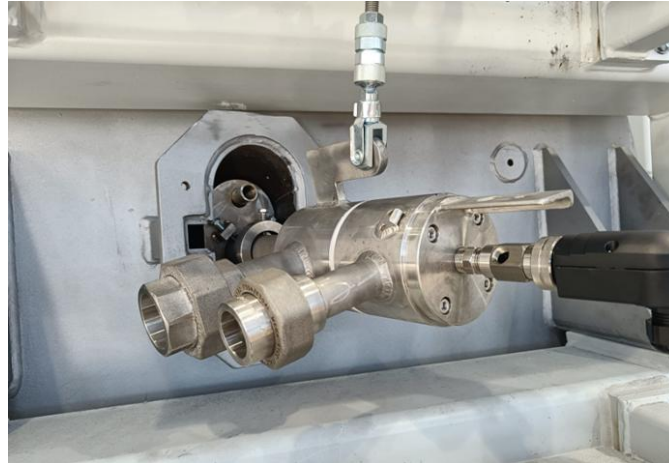


Figure 61: Example of regulation of burner position in a furnace

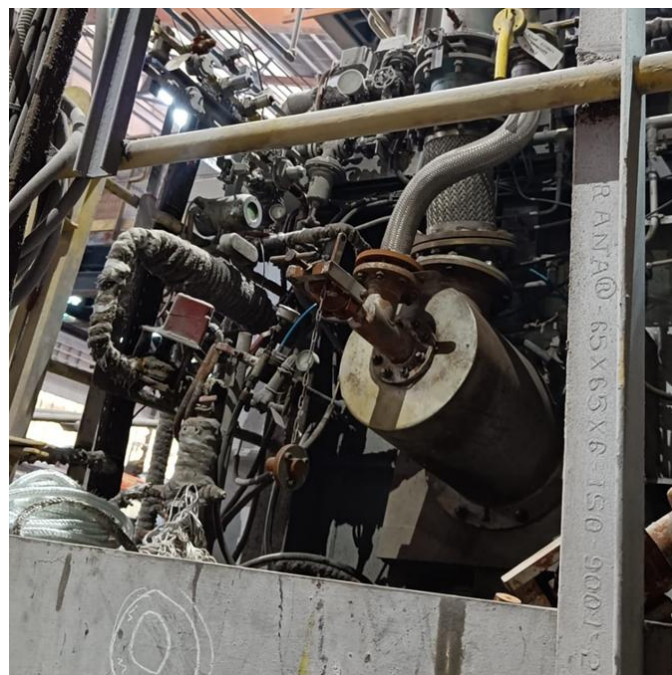


Figure 62: Actual furnace burners at Metlen

5.6 Metlen off-gas system

For the fumes evacuation of the furnace in one of its corners is the fume exit.

5.6.1 Air – Natural gas fumes exit

The off-gas system has a maximum size of 750mm x 1080mm of opening. Considering the maximum fumes flow of 6.780 Nm³/h of fumes (565 natural gas Nm³/h and 6.215 Nm³/h to ensure a stoichiometry of 11:1 to ensure complete combustion of the gas).

The temperature of the fumes flow when going to maximum power could go in a holder furnace at about 1.000°C so the actual fumes flow would be 28.980 Am³/h @ 1.000°C.

With that flow the approximate fumes speed is 9,93 m/s, that is a typical benchmark speed to be compared when going to other fuels or combustion.

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5.6.2 Air – Hydrogen effect

The fumes flow when going with Hydrogen will be different as the needed flow will be 7.065 Nm³/h (1.950 hydrogen Nm³/h and 5.115 Nm³/h to ensure a stoichiometry of 2,6:1 to ensure complete combustion of the gas).

The temperature of the fumes flow when going to maximum power could go in a holder furnace at about 1.000°C so the actual fumes flow would be 33.000 Am³/h @ 1.000°C.

With that flow the approximate fumes speed is 11,31 m/s, that is a typical benchmark speed to be compared when going to other fuels or combustion.

5.6.3 Oxygen – Hydrogen effect

The fumes flow when going with Hydrogen will be different as the needed flow will be 1.860 Nm³/h (1.080 hydrogen Nm³/h and 780 Nm³/h to ensure correct stoichiometry to ensure complete combustion of the gas).

The temperature of the fumes flow when going to maximum power could go in a holder furnace at about 1.000°C so the actual fumes flow would be 8.670 Am³/h @ 1.000°C.

With that flow the approximate fumes speed is 2,97 m/s.

5.6.4 Off-gas conclusion

When going from air-natural gas combustion to an air-hydrogen combustion, the flow of fumes is very similar, slightly higher on the hydrogen combustion but excessively high (13,8% more flue gases). This could lead based on experience to slightly positive pressure on the furnace if the fumes are not capable of being evacuated with enough speed.

For the case of oxyfuel as the volume of fumes descends significantly, the damper of the fumes exit can be closed to whatever opening is necessary at a certain moment.



Figure 63: Off-gas system size

Additionally, the furnace fumes are mixed by design with the air coming from the hood as seen in the above picture, that cool the fumes down naturally, from the temperature of 1.000°C exiting the furnace to a temperature of 400°C approximately that are adequate for the chimney where the fumes are released. The natural draft of the chimney sucks air from the hood and fumes from the furnace and mixes them.

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That effect also mixes the potential 100% water vapour atmosphere coming from the furnace in the case of hydrogen combustion with cold air, obtaining a mix of 50% water vapour and 50% air, that brings down the potential condensation effects that could happen when increasing the water vapour content of the fumes.

5.7 Speira pusher furnace burner and radiant tube retrofit

For the Speira case, the actual burner is a design made by Ebner, the original furnace manufacturer for Speira, with a gross power off 146 kW approx. It is installed in a single ended radiant tube or “SER” type radiant tube. The combustion gases and flame are delivered into the inner ceramic tubes that are located inside the radiant tube so that at the end of the inner ceramic tubes, the combustion gases turn around, transferring the heat to the radiant tube and later to the recuperative burner fins, as can be seen on the next figure.

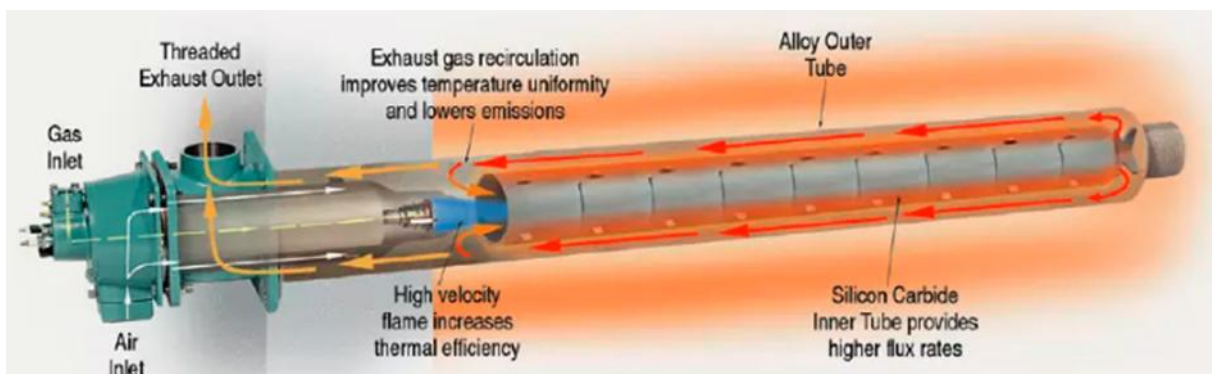


Figure 64: Single ended radiant tube working mode

The burner itself works with 20% combustion air premixed with the fuel, so it is not suitable for hydrogen combustion due to the higher flammability of hydrogen. A new burner is proposed for the application ensuring both an efficient heat recovery and complying with a 100% hydrogen combustion.

The proposed burner would be from the WS brand as they comply with request of efficiency and hydrogen combustion needs. The main data of the burner is shown next.

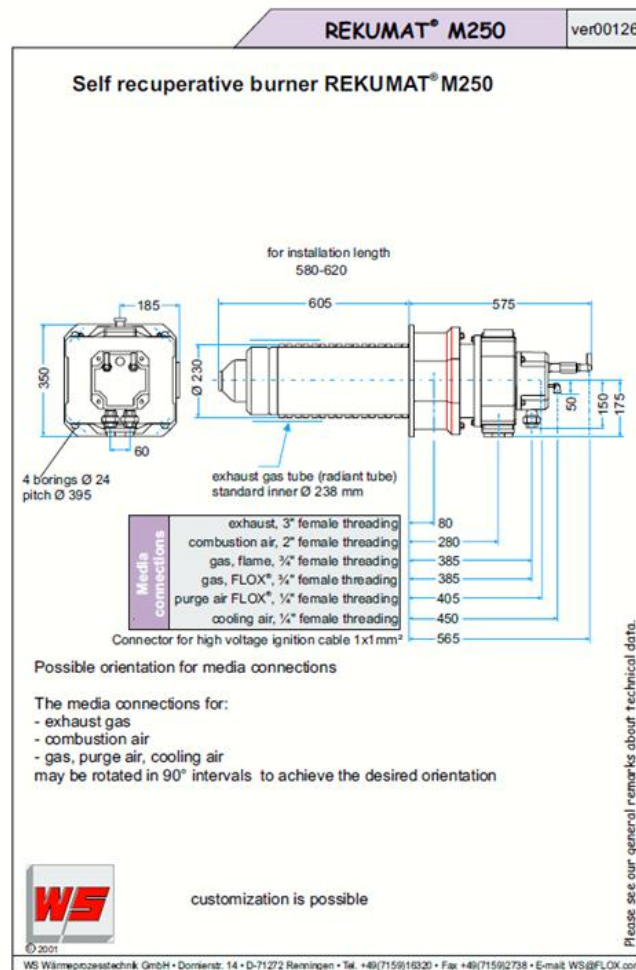


Figure 65: Rekumat M250 data sheet

Assuming an efficiency similar to Ebner as a minimum, the selected burner power should be within the indicated 146 kW. The following burners would then be adequate from a power point of view:

- M250: 120 to 240 kW
- M300: 160 to 300 kW

Another important decision to be taken is related to the existing radiant tube, as it would be in the best interest to keep the same radiant tube. The existing one has a diameter of 310mm and would be too big for the WS burners so an adaptation must be made to the radiant tube.

The recuperative burners have fins as can be seen on the following figure to recover the heat from the combustion gases exiting the radiant tube, and thus the fins need to be very close to the radiant tube inner wall. The required distance depends on each burner but for the M250 is 238mm and for the M300 is 285mm.



Figure 66: Rekumat M250

These sizes are too small for the actual radiant tube and it will affect the overall efficiency and performance of the burner so in order to have an adequate efficiency, the best possible solution that does not imply changing the tube would be to install an adapter tube as the one that can be seen in the picture and that is used by GHI in these occasions. This adapter tube reduces the internal diameter of the radiant tube in the area where the burner is located.



Figure 67: Rekumat installation with a smaller burner

With this the burner power selection is decided and the next steps can be taken.

5.7.1 Burner flame length

Burner flame length has a great relevance in burner selection and placement. In this case it is not so critical as the need is the selection of similarly powered burner to accommodate the existing radiant tubes.

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5.7.2 Burner quantity

The furnace has actually 60 burners in total so it would be necessary to replace all of them to ensure a complete elimination of the fossil fuels used. A partial revamping could be done but it would complicate the controls of the furnace.

5.7.3 Burner location

Burner location will remain the same for the reasons explained that the radiant tube would be kept, and usually this kind of heat treatment furnaces has usually a big quantity of burners in the furnace zones and cannot be really relocated as the available space is very limited due to the high amount of energy needed for heating the aluminium parts in each zone.

The total number of zones in the furnace is 6, with 10 burners per zone, 5 on each side of the furnace.

5.8 Hydrogen gas supply

Based on the calculations done in WP3 and on deliverable D3.1 for the operating conditions of the demonstrators, the needed capacity for hydrogen is calculated and validated.

For the hydrogen gas supply, this project assumes that only air will be used as a comburent for the combustion system as it will be the most adequate to be fitted to the existing radiant tube system. An oxyfuel system inside a radiant tube could radically alter the combustion behaviour and risk damaging the radiant tubes.

The peak hydrogen flow that will be needed in the furnace will be of 3660 Nm³/h of hydrogen.

This consumption assumes that the furnace will be working at full production, as most of the zones in the furnace would be heating the load that enters the furnace and compensating energy losses that take place when the doors are opened for loading or unloading the furnace. It is possible that depending on the load the consumption would be lower, but to ensure the full production worst case scenario must be considered.

As explained in the previous case, the actual capacity of the hydrogen trailers carrying the fuel (assuming again that there is no possible dedicated hydrogen duct for the supply) is approximately 3000 Nm³ to 4000 Nm³ of Hydrogen,

Trailer replacement would need to happen every hour, a very demanding application and with the actual supply of hydrogen, would demand several dedicated trailers to be refilled at the same time other trailers are being used for hydrogen supply.

At a minimum a double trailer set-up would be needed for the supply of hydrogen, a system similar to the presented on the following image that has been provided in collaboration with the partners from Nippon gases.

This is similar to the Metlen case explained above.

5.9 Speira combustion P&ID

5.9.1 Air – Natural gas – P&ID

The P&ID represents the actual status of the Speira pusher furnace, that has the following working principles for air and gas combustion with the current burners:

- Proportion regulator for gas, following air pressure
- Main burner, pilot not needed with the burner power
- One motorized valve controls the entire zone (6 burners)
- No filter for the fumes as they are non-contaminant (only CO₂ emissions)

5.9.2 Air – Hydrogen – P&ID

Switching to hydrogen would imply modifying several elements as has been indicated in the following P&ID that reflects the needed changes or modifications in red. This study assumes can work with 100% hydrogen.

The main elements that change are the following when going with the air-hydrogen combustion:

- A frequency inverter is recommended to be used due to the air flow change, as it will improve consumption and fan adequation for the lesser air needed.
- A safety electro valve to be able to evacuate hydrogen from the gas train is recommended to be installed, as this would allow for the evacuation of the not used gas and reduced the potential risk of leaks from the system.
- A pressure switch between the two electrovalves to ensure no hydrogen leaks on the valves controlling the burner.
- Flow measurement system for both air and hydrogen for a more precise control of the combustion.
- Hydrogen regulation valve to be able to control the flow of hydrogen after installing the new flow control.
- Orifice plates for fine adjustment of the hydrogen into each burner.

When taking into account the existing pipes that are used for natural gas and the new use of hydrogen that would be needed, some of them exceed the recommendation from D3.1 that sets the recommended speed as 60 m/s for Hydrogen. For natural gas, that has also a recommended speed of 20 m/s maximum to avoid the degradation of the pipe and avoiding excessive pressure losses.

In the case of conserving the piping for Hydrogen, the ducts of DN40 would need to be changed to DN 50, as the recommended speed of 60 m/s is exceeded.

HYDROGEN						
Piping			Flow speed			
DN	m	m2	m/s	m/s	m/s	m/s
150	0,15	0,01767146	57,23			
65	0,065	0,00331831		50,79		
40	0,04	0,00125664			67,06	
20	0,02	0,00031416				53,65
Gas conditions						
		Normal	High pres.	Zone 1	Sub Z1	Burner
Pressure	mbar	1013	1093	1093	1093	1093
Flow	Nm3/h	3660	3640,6	606,8	303,4	60,7
Flow	Nm3/s	1,017	1,011	0,169	0,084	0,017

NATURAL GAS						
Piping			Flow speed			
DN	m	m2	m/s	m/s	m/s	m/s
150	0,15	0,01767146	16,10			
65	0,065	0,00331831		14,29		
40	0,04	0,00125664			19,22	
20	0,02	0,00031416				15,38
Gas conditions						
		Normal	High pres.	Zone 1	Sub Z1	Burner
Pressure	mbar	1013	1093	1093	1073	1073
Flow	Nm3/h	1030	1024,5	170,8	87,0	17,4
Flow	Nm3/s	0,286	0,285	0,047	0,024	0,005

Figure 68: Speira furnace gas trains for Hydrogen and natural gas

Increasing the size of the DN40 ducts would reduce the speed as indicated below.

HYDROGEN						
Piping			Flow speed			
DN	m	m2	m/s	m/s	m/s	m/s
150	0,15	0,01767146	57,23			
65	0,065	0,00331831		50,79		
50	0,05	0,0019635			42,92	
20	0,02	0,00031416				53,65
Gas conditions						
		Normal	High pres.	Zone 1	Sub Z1	Burner
Pressure	mbar	1013	1093	1093	1093	1093
Flow	Nm3/h	3660	3640,6	606,8	303,4	60,7
Flow	Nm3/s	1,017	1,011	0,169	0,084	0,017

Figure 69 : Speira furnace recommended ducts for Hydrogen

5.10 Speira furnace modification

5.10.1 Furnace lining modification

As the change would only affect the burner, no change in the lining is expected as the radiant tube in contact with the lining of the furnace will be the same, thus no replacement or modification is expected.

5.10.2 Furnace steelwork modification

The only mechanical modification would be the installation of the burner itself on the radiant tube as some flanges or additional supports could be needed to ensure that the burner is correctly installed, as depending on the burner tip location, it has to be adjusted to keep the same distance to the inner ceramic tubes in order to keep a good combustion running. Altering that distance could result in damage to the inner ceramic tubes.

5.11 Off-gas system

The off-gas system would also be the same that is being used for natural gas as the combustion with hydrogen is quite similar.

When using natural gas the maximum fumes flow of the system is 1.030 Nm³/h of natural gas that corresponds to an air volume of 11.330 Nm³/h to ensure a complete combustion of the gas so the total amount of exhaust gases is 12.360 Nm³/h @ approx. 800°C due to the typical working temperature of 620°C.

The fumes flow when going with Hydrogen will be a maximum of 3.660 Nm³/h of hydrogen that corresponds to an air volume of 9.516 Nm³/h for a total fumes flow of 13.176 Nm³/h @ 800°C, a bit higher fumes flow but that could be processed in the actual exhaust ducts and chimney.

5.11.1 Off-gas emissions

According to the results from the other partners two logical conclusions can be extracted. CO emissions could be reduced to 0 as hydrogen would be used as the main fuel, so any potential emissions could come from volatile organic contents such as oils or similar but probably they would be eliminated.

In regard to the NO_x value it could be expected a slight increase in the emissions as the hydrogen combustion has a higher flame temperature and thus could lead to more emissions, as they depend on the presence of air (nitrogen and oxygen) and the temperature of the flame.

5.11.2 Off-gas conclusion

When going from air-natural gas combustion to an air-hydrogen combustion, the flow of fumes is very similar, slightly higher on the hydrogen combustion. This could lead based on experience to slightly positive pressure on the radiant tubes if the fumes are not capable of being evacuated with enough speed but as the difference is very low no other consequences are expected.

5.12 Numerical study of indirect reheating furnace at Speira

5.12.1 Introduction

The numerical simulations in this task are concerned with the indirectly fired aluminium reheating furnace at Speira Hamburg site. After casting, the aluminium slabs are stored in a buffer and from there are charged into a reheating furnace, where the slabs are preheated for hot rolling. The hot rolling mill at Speira is alternately fed by one directly fired and one indirectly fired reheating furnace. Starting from a fully charged furnace with slabs heated up to the desired temperature for hot rolling, the rolling mill is fed with one preheated slab at a time. For each preheated slab discharged from the furnace, another cold slab is charged until all preheated slabs left the furnace, and the new stack consists of cold to partially preheated slabs. The furnace then preheats the stack of slabs while the rolling mill is fed by the second reheating furnace.

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The present study is concerned with the indirect reheating furnace. The aluminium slabs are standing upright on skids, which are travelling through the furnace from the charging to discharging side. The skids are moved by pushing onto each other. The slabs are then convectively heated by an air stream which is circulated by fans to stream upwards through the stack of slabs and from the furnace roof is guided towards the side walls, where it passes radiant tubes while streaming downwards through a channel shielding the furnace chamber from the radiant tubes. From there, the heated air is guided towards the furnace chamber where it is heating the slabs. The furnace atmosphere temperature reaches from 300°C to 600°C depending on the cycle and furnace zone. The furnace is equipped with a total of 60 radiant tubes, 30 along a single row on each side, organized in 6 heating zones in the direction of slab movement. The radiant tubes are of single-ended-type and are installed hanging from the furnace roof. Inside each radiant tube, there is a partially premixed, self-recuperative natural gas burner from furnace manufacturer Ebner installed from the top. The flame is confined in the flame tube which is fixed concentrically in the radiant tube. Outside the flame tube, flue gases are guided back towards the burner, where they are partially recirculated into the reaction zone within the flame tube by suction from the flame. The remaining flue gas leaves the radiant tube through the recuperator, where it preheats the incoming combustion air.

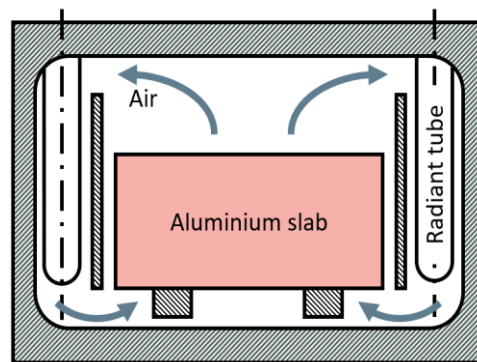


Figure 70: Schematic of indirectly fired aluminium slab reheating furnace

In this study, the heating system is investigated for the effects of oxygen enrichment of the combustion air and stepwise substitution of the natural gas by hydrogen including blends of both fuels. The evaluation focuses on the efficiency of the heating system and the effect on maximum temperatures experienced in the flame and the heating system, namely the temperatures at the burner tip, the radiant tube, and the flame tube.

5.12.2 Methodology

A computational fluid dynamics (CFD) model is derived from the physical system with the definition of a computational domain, a numerical grid, and models for the considered phenomena. The boundary conditions are set according to the defined simulation cases covering air enrichment by oxygen up to 50% by volume with the currently installed burner and the fuel switch from natural gas to hydrogen with a retrofitted fuel-flexible burner. The natural gas at the site is composed of over 90% of methane, the exact composition is taken from the grid operator in Hamburg for the month of June 2025 as given in the next table. From this month the operation data is analyzed to derive the boundary conditions for simulation. Hydrogen is assumed to have no impurities.

Table 13: Natural gas composition at the Speira Hamburg site

LHV [MJ/kg]	X_{CH_4} [%]	$X_{C_2H_6}$ [%]	$X_{C_3H_8}$ [%]	X_{CO_2} [%]	X_{N_2} [%]
48.741	93.80	4.51	0.74	0.50	0.45

5.12.2.1 Computational domain

As the study is concerned with changes and modifications of the combustion system rather than the entire furnace, the simulation domain is chosen to be a single radiant tube. The surrounding of each is assumed to

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not be affected by manipulation of the oxidizer or fuel composition, as the combustion is confined within the radiant tube.

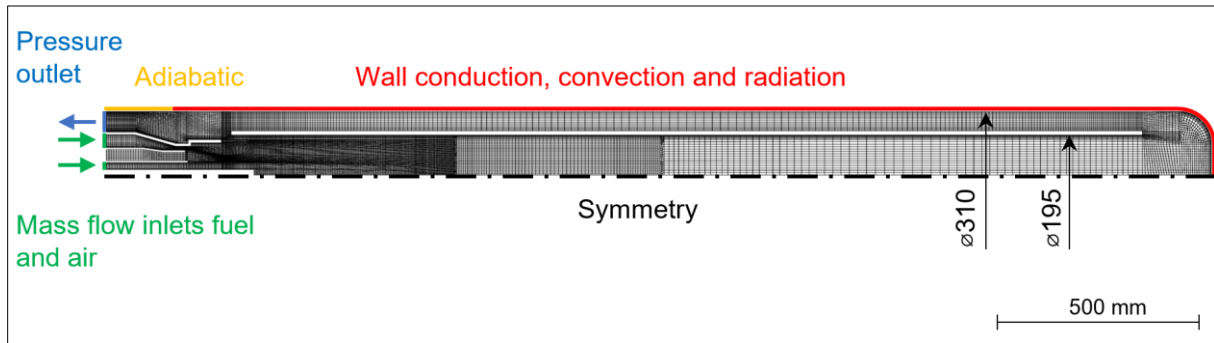


Figure 71: Computational mesh with boundary conditions

The simulation domain exploits the rotational symmetry of the radiant tube and burner by reduction of the geometry to two dimensions and introduction of a symmetry axis at the centerline of the physical system. The computational mesh is shown in the previous figure. Fuel is injected via the central lance with a specified mass flow, composition and at ambient temperature. 20% of the combustion air is premixed to the fuel and enters through the same inlet. The remaining 80% of combustion air is injected through a separate channel after being preheated in the recuperator. The preheated air temperature is computed from the relation

$$T_{\text{air,preh}} = T_{\text{amb}} + \varepsilon(T_{\text{flue}} - T_{\text{amb}})$$

with relative air preheating of $\varepsilon = 0.65$. The preheated air temperature is updated based on the flue gas temperature at the outlet at every iteration during the solution process. The outlet is characterized by the specification of static pressure, which is set to ambient pressure of $p_{\text{amb}} = 101.325 \text{ Pa}$. The simulation accounts for conjugate heat transfer in the solids. The Fourier equation is solved in the burner and the flame tube. At the radiant tube boundary, a mixed condition is specified accounting for heat conduction through a wall with convection and radiation on the outside. The wall is meshed by one shell layer allowing for heat conduction in the plane of the radiant tube surface. The ambient temperature is set based on zone temperature measurement. After furnace charging with cold slabs is completed, the furnace is heated at its nominal power capacity for about two hours, depending on the specifics of the operation strategy. During the heating, temperatures rise in a linear manner in all zones. From historical production data, a representative heating cycle is identified from which the average temperature of each zone during heating is taken as the ambient temperature for the thermal boundary condition to the simulation.

A second domain is established where the self-recuperative burner Rekumat M250S from WS Thermal Process Technology is virtually retrofitted allowing for fuel-flexible operation. The radiant tube and flame tube are kept from the original system, to ensure compatibility to the furnace. In contrast to the currently installed burner, the retrofitted burner does not feature partial air premixing. While the burner is capable of variable fuel staging by fuel injection into a combustion chamber, only the FLOX mode intended to promote flameless combustion conditions is considered in the present study. In this mode, fuel is injected via a central lance, and preheated air is entering through an annular gap between the combustion chamber and the fuel lance.

The domain is discretized using a structured mesh with prism layer cells resolving the boundary layer down to $y^+ \sim 1$ at the first cell. The mesh is resolved finer in the reaction zone to appropriately capture sharper gradients and is stepwise coarsened downstream to yield a computationally efficient mesh. Mesh independency is reached with mesh sizes of 15k cells for the currently installed burner and 28k cells for the retrofitted burner. The difference in required cell count is due to higher geometrical complexity of the WS burner.

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5.12.2.2 Numerical models

Turbulence is modelled by the k - ω SST model, which is chosen over the k - ϵ model for its superior performance on the prediction of wall bounded turbulent flows. The species transport model is used with the Eddy Dissipation Concept (EDC) for turbulence chemistry interaction with the default coefficients for reacting volume fraction and time scale. Chemistry integration is accelerated by in-situ adaptive tabulation (ISAT) with a relative error tolerance of $1e-4$.

Table 14: Physical phenomena and corresponding numerical models

Phenomena	Model
Turbulence	k - ω SST
Turbulence chemistry interaction	Eddy Dissipation Concept
Chemical kinetic mechanism	SkeleCHy
Radiation	Discrete Ordinate Method
Gas emissivity	Weighted Sum of Gray Gases

The radiative transfer equation is solved using the Discrete Ordinate Method (DOM) with a 4x4 directional discretization per octant and 3x3 pixelation of the cell surfaces. The gas absorption coefficient is determined from a full-spectrum k -distribution based weighted sum of gray gases model (WSGGM), which was calibrated for blends of hydrogen and hydrocarbon fuels in Task 1.4 of the present project. The simulations are performed using the coupled solver with double precision in the commercial software Ansys Fluent release 2024 R2.

5.12.2.3 Operating conditions

Within the task, three studies are performed to investigate the behaviour of the radiant tube depending on the furnace zone in which it is located, the enrichment of the combustion air by O_2 , and the stepwise substitution of natural gas by H_2 . The radiant tubes are distributed over the entire length of the furnace over 6 separately controlled zones. As the furnace atmospheres temperature increases from the charging to the discharging side of the furnace, the radiant tubes experience different temperatures depending on their location. To conclude from the results of single radiant tube CFD simulations to the behaviour of the entire furnace, the radiant tube is simulated in all 6 zones, each with the ambient temperature taken from measured data from regular operation in a representative state. The boundary conditions represent the system in its original state and may be taken from the next table. The thermal power is 146.2 kW, fuel is natural gas and the air-fuel equivalence-ratio is 1.15. The combustion air is not enriched by O_2 and 20% of the air volume flow is being premixed to the fuel.

Table 15: Simulation cases furnace zone study.

Case	P_{thermal} [kW]	$X_{H_2, \text{fuel}}$ [%]	λ [–]	Air premixing [%]	$X_{O_2, \text{air}}$ [%]	Furnace zone
1.1	146.2	0	1.15	20	20.9	1
1.2						2
1.3						3
1.4						4
1.5						5
1.6/2.1						6

For consecutive studies, the radiant tube is investigated within zone 6. This zone is assumed to be most critical as the system experiences the highest ambient temperature and consequently, the highest thermal load on the components. The consecutive study is concerned with O_2 enrichment of the combustion air. This measure potentially comes with fewer required modifications compared to switching the fuel and is expected to increase the thermal efficiency by reducing the amount of nitrogen, which is not contributing to heat release. To investigate the effect on the system, 8 cases are set up as listed in the next table. For each fuel – natural

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gas and hydrogen – the O₂ content is varied to 20.9%, 30%, 40%, and 50% by volume. In this study, the burner remains unmodified.

Table 16: Simulation cases oxygen enrichment study

Case	P_{thermal} [kW]	$X_{\text{H}_2,\text{fuel}}$ [%]	λ [–]	Air premixing [%]	$X_{\text{O}_2,\text{air}}$ [%]	Furnace zone
2.1	146.2	0	1.15	20	20.9	6
2.2		0			30	6
2.3		0			40	6
2.4		0			50	6
2.5	146.2	100	1.15	0	20.9	6
2.6		100			30	6
2.7		100			40	6
2.8		100			50	6

Eventually, the effect of stepwise substitution of natural gas by H₂ is investigated. To this end, a fuel-flexible burner is virtually retrofitted which can burn arbitrary mixtures of natural gas and H₂. The fuel H₂ content is varied to 0%, 50%, 80%, and 100% by volume, as given in the next table. The steps in H₂ enrichment are chosen to represent more even steps in thermal power contribution rather than volume fraction in the fuel gas.

Table 17: Simulation cases fuel study

Case	P_{thermal} [kW]	$X_{\text{H}_2,\text{fuel}}$ [%]	λ [–]	Air premixing [%]	$X_{\text{O}_2,\text{air}}$ [%]	Furnace zone
3.1	146.2	0	1.15	0	20.9	6
3.2		50				6
3.3		80				6
3.4		100				6

5.12.3 Results

The result section is organized in the three studies of furnace zone, O₂ enrichment, and fuel switch. The focus is on the thermal efficiency and thermal load on the equipment.

5.12.3.1 Zone study

The average zone temperature during the heating cycle that is used in the boundary condition at the radiant tube surface is given at the right axis of the next figure. The zones are indicated in order from charging to discharging side. The zone temperatures vary from 719 K at the charging side to 806 K at the discharging side and monotonically increase in between. In zones 3, 4, and 5 the temperatures closely agree with deviations less than 5 K.

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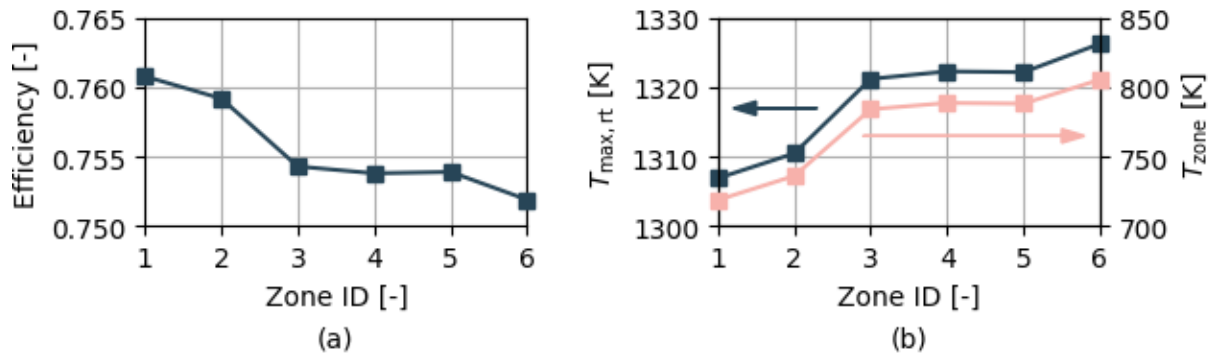


Figure 72: Thermal efficiency (a), maximum radiant tube temperature and zone temperature (b) for each furnace zone

Qualitatively, the evolution of the zone temperature is followed by the radiant tube surface temperature. The maximum surface temperature is experienced at the radiant tubes tip and is shown for the different furnace zones at the left axis of the previous figure. The surface temperature is mainly driven by the balance in heat exchange of the radiant tube with its surrounding via thermal radiation. Increased ambient temperature imposes an increased radiative heat flux to the radiant tube, increasing its surface temperature and with it the emitted radiative heat flux. As the emitted radiation of a surface is proportional to the 4th power of temperature and the radiant tube has more than 500K higher temperature than the ambience, the difference in maximum temperature of the radiant tube surface is small compared to the difference in zone temperature.

Along with the altered temperature distribution of the radiant tube surface and its environment comes an altered thermal efficiency of the system. The thermal efficiency of the radiant tube may be defined as

$$\eta = \dot{Q}_{furnace} / \dot{H}_{fuel},$$

where $\dot{Q}_{furnace}$ is the useful heat that is transferred to the furnace via the radiant tube surface and $\dot{H}_{fuel}$ is the enthalpy introduced by the fuel based on the lower heating value. It is observed that increasing zone temperature has an inverse effect on the radiant tubes efficiency with efficiency dropping from 76.1% to 75.2% from zone 1 to zone 6. As the effects of zone temperature on the radiant tubes temperature distribution and the thermal efficiency are in the order of 1% for both quantities, it is assumed that simulation results from single zones can be used to conclude on the behaviour of the complete furnace. To investigate the influence of air enrichment by O_2 and fuel enrichment by H_2 in the following studies, only one radiant tube in zone 6 is considered. The zone is chosen for the highest temperatures and consequently, the highest thermal load on the equipment, representing the most critical condition.

5.12.3.2 Oxygen enrichment study

Enrichment of the combustion air with O_2 is expected to increase the efficiency of the system while increasing the thermal load on the equipment as well. The CFD simulations performed in this study are meant to quantify both effects to allow for an assessment of the measure. In the following, results from cases 2.1-2.4 are presented and discussed.

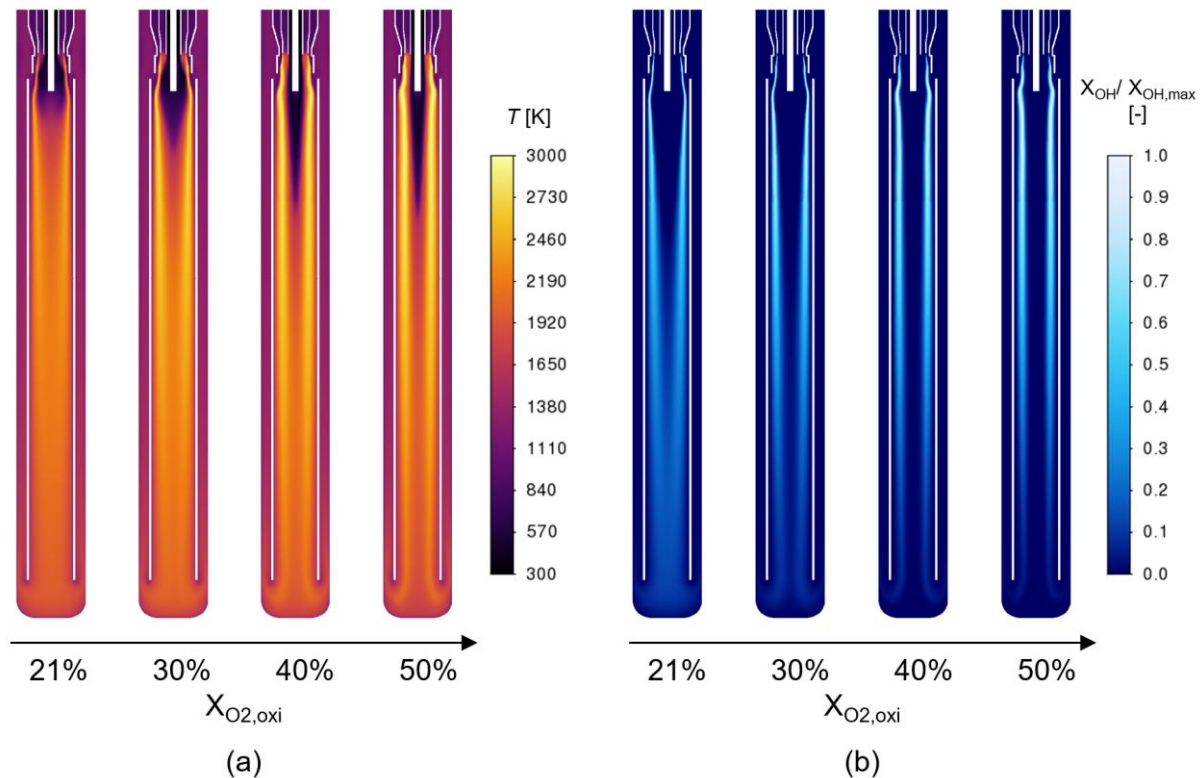


Figure 73: Gas temperature (a) and OH content (b) distributions in the radiant tube over combustion air O₂ enrichment up to 50% by volume

The gas temperature distribution is given in the previous **Fehler! Verweisquelle konnte nicht gefunden werden.** (a) for 21%, 30%, 40%, and 50% O₂ enrichment of the combustion air. The effect of increased gas temperature with O₂ enrichment is clearly identified in the reaction zone. The most significant rise in reaction zone peak temperature is experienced from 21% to 30% of O₂ content in the combustion air. In the previous **Fehler! Verweisquelle konnte nicht gefunden werden.** (b), the distribution of the OH radical by relative volume fraction is given for the same cases to indicate the location of the reaction zone. A thickening of the reaction zone is observed for increasing O₂ enrichment. Downstream the flame, the reaction zone appears more distinguished the higher the O₂ enrichment. At reference conditions without O₂ enrichment, the flame is attached to the burner. Increased O₂ content in the oxidizer increases the reactivity of the mixed gases and the flame speed, respectively, while the velocity of the combustion air is decreased due to the fewer required volume flow. Consequently, the attachment of the reaction zone remains unaffected.

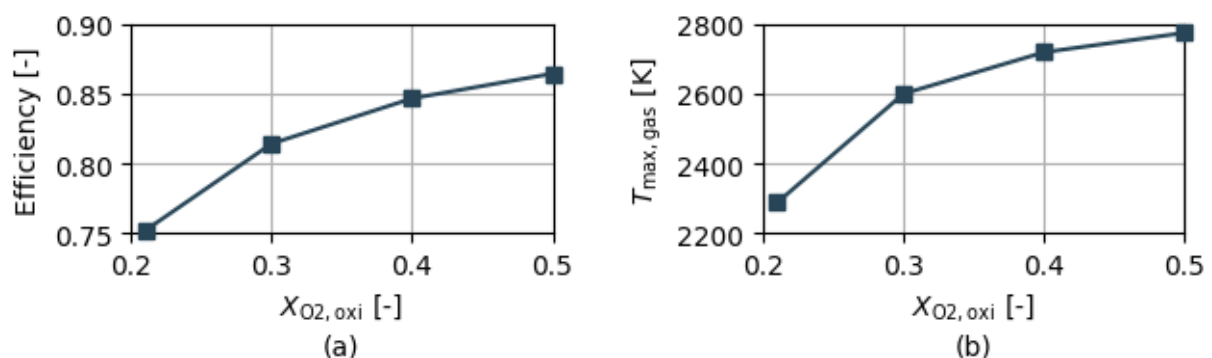


Figure 74: Thermal efficiency (a) and maximum gas temperature (b) over combustion air O₂ enrichment

The thermal efficiency over O₂ enrichment is given in the previous **Fehler! Verweisquelle konnte nicht gefunden werden.** (a). For the considered cases, the thermal efficiency rises from 75.2% without enrichment to 86.5% at 50% O₂ enrichment. The evolution shows a saturating behaviour, where saturation is not reached

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at 50% O₂ enrichment yet, but the increase becomes smaller the higher the enrichment. The efficiency increase is related to the reduced dilution of the flue gas by inert N₂, which increases the flame temperature and hence, the potential for heat transfer. To quantify the effect, the maximum gas temperature is given in the previous **Fehler! Verweisquelle konnte nicht gefunden werden.** (b). It rises from 2288 K to 2776 K over 21% to 50% combustion air O₂ content. Again, the maximum temperature shows a saturating behaviour over the enrichment.

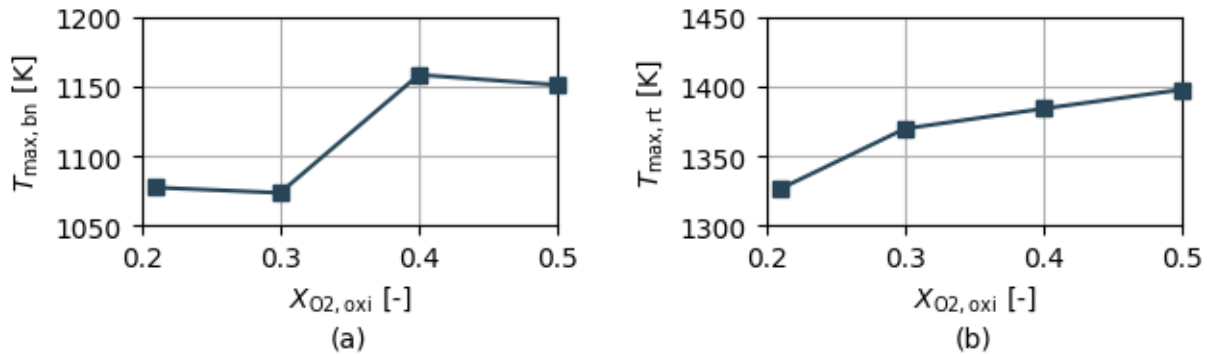


Figure 75: Maximum temperature in the solid bodies of burner (a) and radiant tube (b)

Besides the favourable effect of increased thermal efficiency, the increased gas temperature causes elevated temperature in the equipment and consequently imposes an increased thermal load on the burner and the radiant tube. The maximum temperatures of the solid bodies of burner and radiant tube are given in the previous **Fehler! Verweisquelle konnte nicht gefunden werden.** (a) and (b). The maximum temperature of the burner predicted by the CFD is to be interpreted with caution, as it is sensitive to the specific attachment and dynamic of the flame near the burner nozzles. The steady state axisymmetric 2D RANS simulation is expected to not capture the detailed behaviour of the flame entirely, as the assumptions of symmetry and steady state suppress potential instabilities. However, a global trend of increasing maximum temperature at the burner is observed from 1077 K to 1151 K over the considered cases. The maximum radiant tube temperature rises from 1326 K to 1398 K at 21% to 50% O₂ content and shows a monotonic increase in between.

Besides the presented cases 2.1 to 2.4, the O₂ enrichment study with the original equipment is performed with hydrogen fuel as well (see cases 2.5 to 2.8 in the previous **Fehler! Verweisquelle konnte nicht gefunden werden.**). Applying the same partial air premixing of 20% to hydrogen fuel results in the hazard of flashback, as a hydrogen/air mixture is more reactive and has a wider range of ignition limits compared to natural gas/air. Consequently, no air premixing is employed for the investigation of hydrogen fuel in the present heating system. Together with lower fuel density and higher flame velocity of hydrogen compared to natural gas, the aerodynamics of the combustion are altered significantly, and the simulated operating condition is far beyond the intended design point. For cases 2.6 and 2.7 with 30% and 40% oxidizer O₂ content, no stable solution is obtained with the presented simulation setup. To study the effect of hydrogen fuel on the system, a fuel flexible burner is virtually retrofitted.

5.12.3.3 Fuel study

Keeping the radiant tube and flame tube unchanged, a fuel-flexible recuperative burner Rekumat M250 from WS Thermal Process Technology is virtually retrofitted to perform the simulations with 0%, 50%, 80% and 100% H₂ admixture to the fuel by volume as given in the previous **Fehler! Verweisquelle konnte nicht gefunden werden.** The burner features fuel staging, where the primary fuel gas is injected radially within a combustion chamber and the secondary fuel gas is injected axially through a central lance. Flue gas is partially recirculated through the gap between burner head and flame tube to dilute the secondary reaction zone which develops inside the flame tube. The present study is performed with 100% fuel staging, where the entire fuel is supplied via the central gas lance. The desired combustion regime is termed flameless oxidation/FLOX by the supplier.

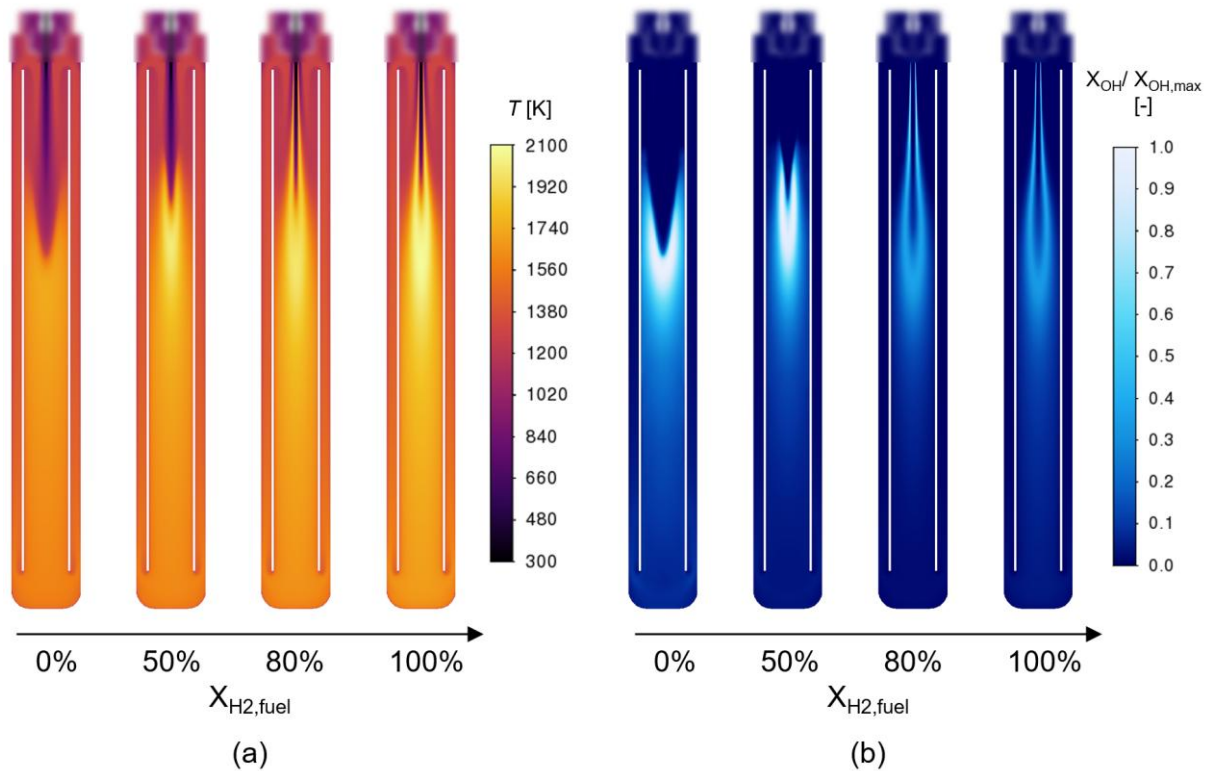


Figure 76: Gas temperature (a) and OH content (b) distributions in the radiant tube over fuel H₂ by volume

The gas temperature distribution is given in **Fehler! Verweisquelle konnte nicht gefunden werden.** over the H₂ content of the fuel. For natural gas fuel, the reaction zone is located at about one third of the flame tube length, as indicated by the sharp increase in temperature. The cone-shape of the flame suggests a premixing of fuel and oxidizer before ignition. Furthermore, the reactants are diluted by recirculated flue gas with recirculation factors $K = \dot{m}_{flue, recirc} / (\dot{m}_{fuel} + \dot{m}_{air})$ from 1.56 to 1.65 for H₂ and natural gas fuel, respectively. For 50% H₂ admixture by volume, the reaction zone moves upstream, and for 80% and 100% H₂ the flame attaches to the fuel nozzle, appearing as a diffusion flame, where flue gas dilutes the reaction zone further downstream. The location of the reaction zone can be judged from the OH radical distribution given in the previous **Fehler! Verweisquelle konnte nicht gefunden werden.** (b), where the flame attachment from 80% H₂ on is indicated by OH radical appearance in a thin layer right from the fuel nozzle.

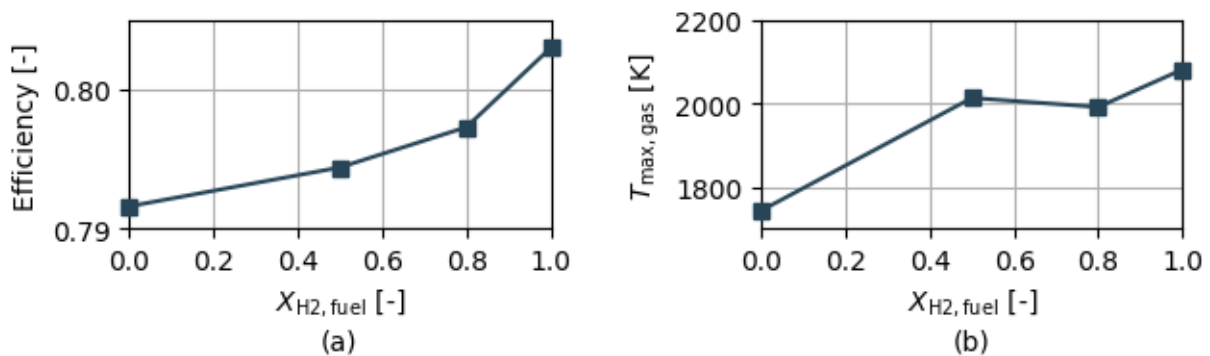


Figure 77: Thermal efficiency (a) and maximum gas temperature (b) over fuel H₂ by volume

The thermal efficiency is given in the previous **Fehler! Verweisquelle konnte nicht gefunden werden.** (a). It is increased by 1.1% from 79.2% to 80.3% when switching the fuel from natural gas to H₂. Due to the decreased air demand, the combustion of H₂ produces fewer flue gas volume at equal thermal power when compared to natural gas. Consequently, the residence time of flue gas in the radiant tube is increased, more heat is

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transferred from the gas to the tube and to the furnace eventually. The enthalpy leaving the system via the flue gas stream is then reduced, increasing the thermal efficiency of the system when fired with higher contents of H_2 in the fuel.

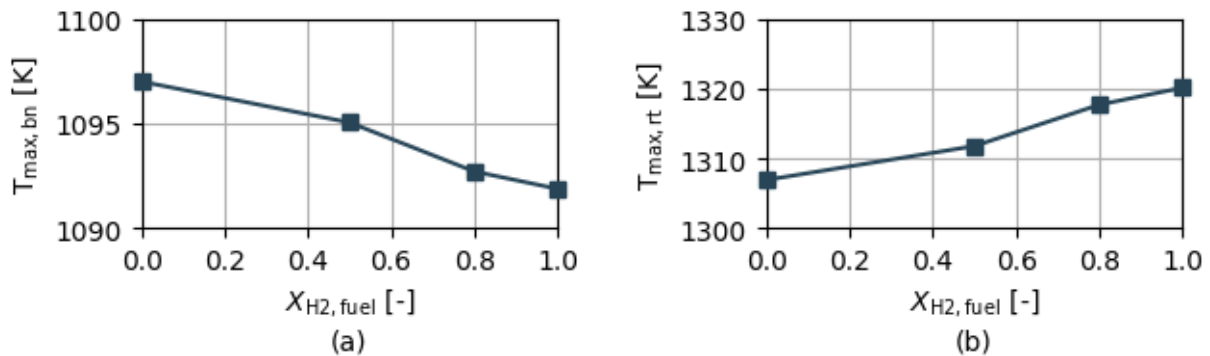


Figure 78: Maximum temperature in the solid bodies of burner (a) and radiant tube (b) over fuel H_2 by volume

The maximum temperature at the burner and the radiant tube are given in the previous **Fehler! Verweisquelle konnte nicht gefunden werden.** (a) and (b). The maximum burner temperature decreases from natural to H_2 firing from 1097 K to 1092 K. Due to the downstream location of the reaction zone and heat release, respectively, the hotspot does not develop at the fuel lance or the combustion chamber, which are being cooled by the streams of unburnt gases, but is found at the burner housing, which is mainly heated from the flue gases guided towards the recuperator. As mentioned in the discussion of thermal efficiency in the previous section, the flue gas that is leaving through the outlet carries fewer heat in the case of H_2 combustion. Consequently, the burner housing experiences slightly reduced maximum temperature. The maximum temperature of the radiant tube, however, increases with fuel H_2 content. As in the O_2 enrichment study, the hotspot is located at the radiant tubes bottom. However, when compared to the originally installed equipment, the peak temperature is reduced with natural gas fuel. The radiant tube surface temperature distribution is more homogeneous with the retrofitted burner, due to an increase in flue gas recirculation.

5.12.4 CFD Conclusion

Three studies are performed on a single radiant tube in Speira reheating furnace for aluminium slabs. The furnace zone in which the radiant tube is located influences the performance through altered ambient temperatures. It is found that the thermal efficiency decreases in the hotter zones, while the maximum radiant tube surface temperature increases. The difference of both quantities between the coldest and hottest zone is in the order of 1% and it is concluded that for the consecutive studies a consideration of a single zone is sufficient to draw conclusions on the entire furnace performance. An increase of O_2 content in the combustion air yields significant improvements in thermal efficiency of up to 10% for O_2 enrichment to 50% by volume.

The thermal load on the equipment is increased at the same time with maximum temperature at the radiant tube surface rising by 70 K. While the specific effect on the radiant tube lifetime goes beyond the scope of the present study, it is concluded, that O_2 enrichment has an adverse effect on radiant tube lifetime. For investigation of the system with H_2 enriched and pure H_2 fuel, a fuel-flexible self-recuperative burner is virtually retrofitted and placed inside the radiant tube. Switching fuel from natural gas to H_2 yields thermal efficiency gains of about 1.17%. The flame is lifted from the burner head for natural gas and 50% fuel H_2 and attaches at higher H_2 enrichment of 80% and 100%. The maximum temperature at the burner is reduced by 5 K from natural gas to H_2 and the maximum radiant tube surface temperature is increased by 13 K. To conclude, the combustion air enrichment by O_2 comes along with a significant increase of thermal efficiency while increasing the thermal load on burner and radiant tube. The switch from natural gas to H_2 fuel is enabled by a retrofit of a fuel-flexible burner. Thermal efficiency is increased by 1% and the maximum temperatures of burner and radiant tube are not significantly altered.

5.13 Conclusions and KPI effect with hydrogen

- Gas consumption: According to WP5, tasks 2 and 3 as well as other test done the last years with a reverberatory furnace, the consumption of the furnace would be the same or even slightly lower when using hydrogen. So for example instead of the typically expected for a furnace of this size of 600 kWh to 700 kWh when using natural gas for example, it could be reduced in a 5% to 10%. When using oxyfuel the reduction in consumption would be expected to be at least 50%.
- NOx emissions according to the other tasks would be increased when using the same burner with hydrogen as fuel. When switching to oxyfuel however, an overall reduction would be expected in terms of net NOx emissions, with them being a bit higher when using 100% H₂ and lower when using 100% NG.
- Off-gas: Off-gas emissions and quantity will be similar when switching fuel to hydrogen with the same burner, with a higher water vapour contents but it should not pose a risk due to the dilution with air and relatively high temperature of the fumes leaving the furnace. When switching to oxyfuel the quantity of fumes would be lower but well within the acceptable working parameters of the furnace.
- Burner: The actual burner could be used for hydrogen as long as Bloom confirms it's 100% operability in their lab in due time. If not the oxy-fuel option is completely viable. In the case of the pusher furnace the burners would need to be replaced with recuperative air-hydrogen burners.
- Piping: For using the actual burner, the piping has to be modified to comply with the standard set in WP3 in terms of gas speed in the ducts.
- An increase of O₂ content in the combustion air of a radiant tube yields significant improvements in thermal efficiency of up to 10% for O₂ enrichment to 50% by volume.
- Switching fuel from natural gas to H₂ yields thermal efficiency gains of about 1.17% in a radiant tube.
- The maximum temperature at the burner is reduced by 5 K from natural gas to H₂ and the maximum radiant tube surface temperature is increased by 13 K.

6 Annealing furnace – TME

6.1 Introduction

Toyota Motor Europe (TME) carried out the retrofit and demonstration of a hydrogen-ready burner system in an industrial annealing furnace used for the heat treatment of aluminium engine components. The objective of the trials was to assess the technical feasibility, safety, and environmental benefits of replacing natural gas with hydrogen blends in existing manufacturing equipment while maintaining production requirements. The demonstration forms part of the wider project objective of reducing CO₂ emissions from energy-intensive industrial processes through the adoption of hydrogen technologies.

The selected furnace is a rotary artificial ageing (T5) furnace operating in serial production conditions. The furnace is used for heat treatment of aluminium engine components and operates at a typical process temperature of approximately 230°C. The installation is equipped with a single burner rated at approximately 170 kW and processes approximately 5,000 tonnes of components annually.

To enable hydrogen operation, a hydrogen-ready burner supplied by Fives was installed. The burner is capable of operating with natural gas, hydrogen, or any intermediate blend ranging from 0% to 100% hydrogen. The burner design incorporates separate fuel injection nozzles for natural gas and hydrogen, allowing safe and flexible fuel switching during the trials. The installation therefore provides a practical demonstration of how existing industrial furnaces can be retrofitted to support future low-carbon fuels.

A summary of the changes and characteristics of the actual retrofitted can be found on deliverable D5.1

The following targets are set for these studies:

- Assess the technical feasibility, safety, and environmental benefits of replacing natural gas with hydrogen blends in existing manufacturing equipment while maintaining production requirements. The demonstration forms part of the wider project objective of reducing CO₂ emissions from energy-intensive industrial processes through the adoption of hydrogen technologies.
- Analyze, reduce risks and improve the safety of the hydrogen usage in a furnace located in the middle of a production plant.
- Simulate and validate a new burner for low temperature firing application in aluminium annealing processes.

6.2 Furnace retrofit and hydrogen Infrastructure

The existing natural gas system was retained and integrated with a newly developed hydrogen supply system. The valve train was designed to accommodate natural gas, hydrogen, and blended fuel operation. Flexible pipework connected the new hydrogen infrastructure to the burner while maintaining compatibility with the existing furnace controls and safety systems.

For the demonstration campaign, hydrogen was supplied using high-pressure hydrogen cylinders positioned inside the building. The cylinders were connected to a dedicated hydrogen valve train and pressure reduction system before being routed to the burner. This approach allowed hydrogen testing without requiring a permanent hydrogen distribution network, which is currently unavailable at the site.

The design of the hydrogen piping and valve train was supported by simulations carried out within the HyInHeat programme. Due to the lower density and different flow characteristics of hydrogen compared with natural gas, dedicated sizing calculations were necessary to ensure safe operation and adequate flow rates at all blending levels.

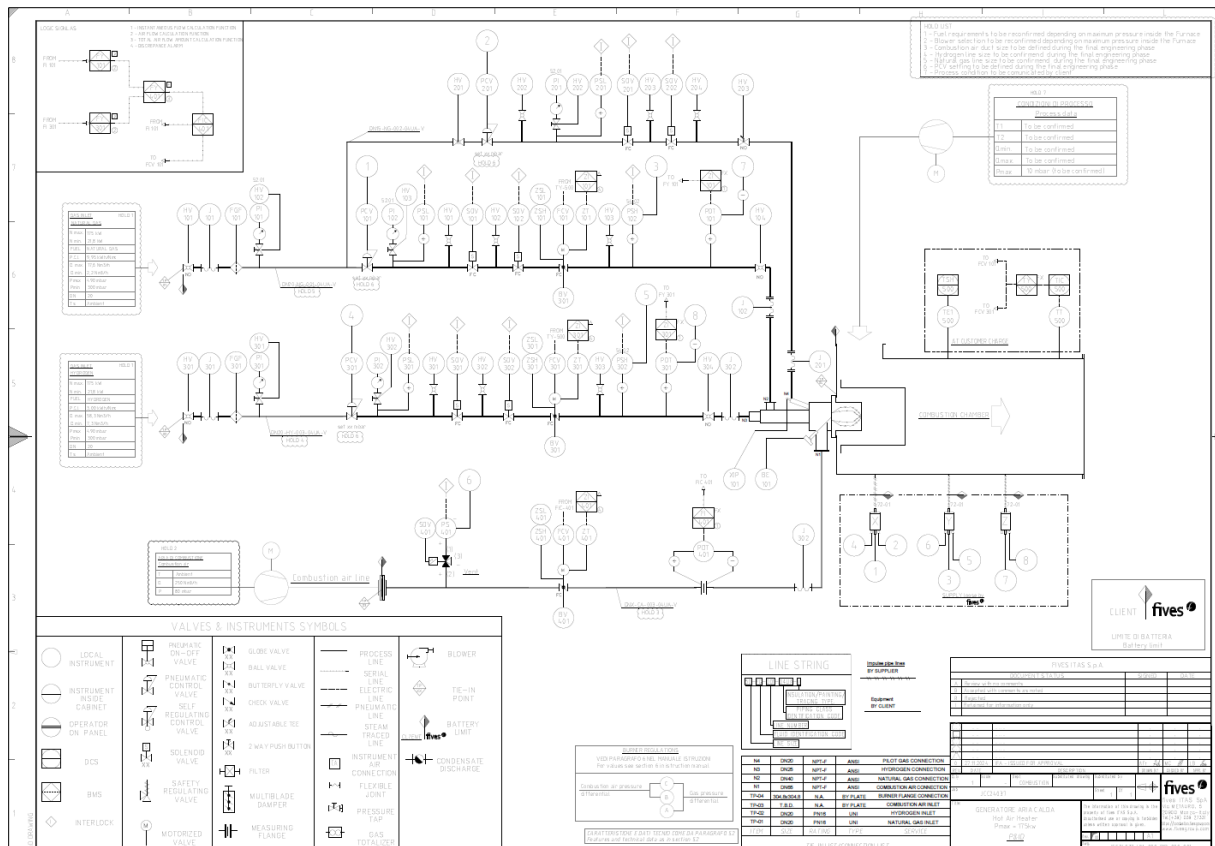


Figure 79: PID of the installation at TME in Poland

The furnace is for mass manufacturing therefore; the retrofit and tests could be carried out during the summer shutdown due to safety requirements. The safety preparations took place from beginning of 2024 to ensure that all in accordance with H&S of Toyota.

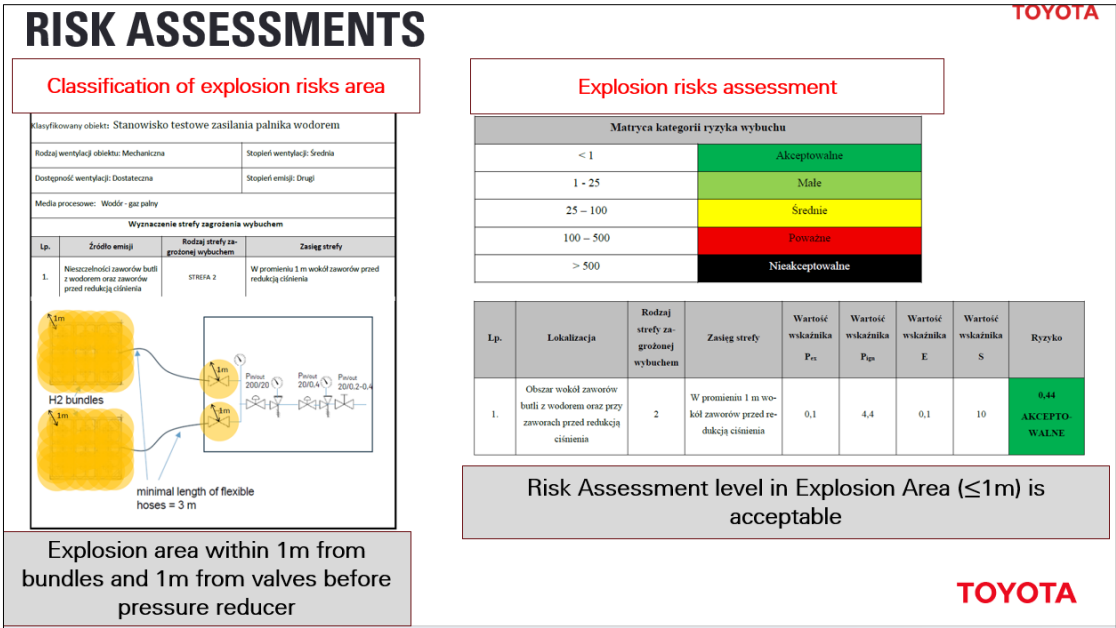
6.3 Safety Preparations

Since the furnace is used in mass-production operations, all retrofit activities and testing campaigns were carefully planned to minimise disruptions to manufacturing while ensuring full compliance with Toyota Health & Safety requirements. The installation work and testing activities were therefore scheduled during the annual summer shutdown period, when production equipment could be safely modified and inspected.

Safety planning began in early 2024 and involved collaboration between TME, TMMP, burner suppliers, safety specialists and HyInHeat project partners. Detailed hazard assessments were conducted to evaluate hydrogen-specific risks, including:

- Explosion risk classification of the installation area.
- Quantitative explosion risk assessment.
- Supplier-side validation and VTO activities.
- Development of dedicated hydrogen handling procedures.
- Installation of temporary and permanent safety zones.

Additional grounding, antistatic clothing requirements and spark-resistant tools. Special attention was given to compliance with hydrogen-related safety standards and explosion protection requirements. The project consortium performed dedicated analyses of hydrogen infrastructure and prepared the required documentation to support safe industrial deployment.



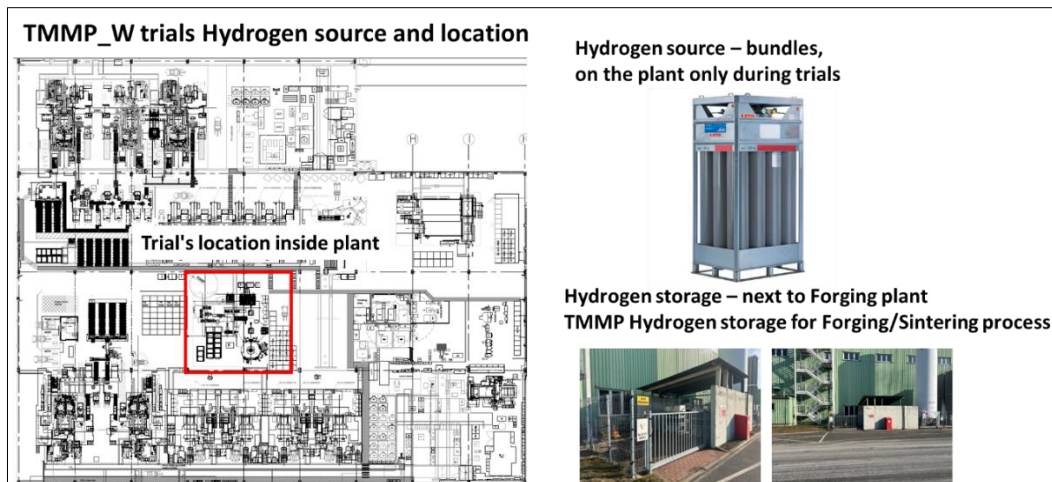


Figure 82: Location of the trials and H2 bottle storage

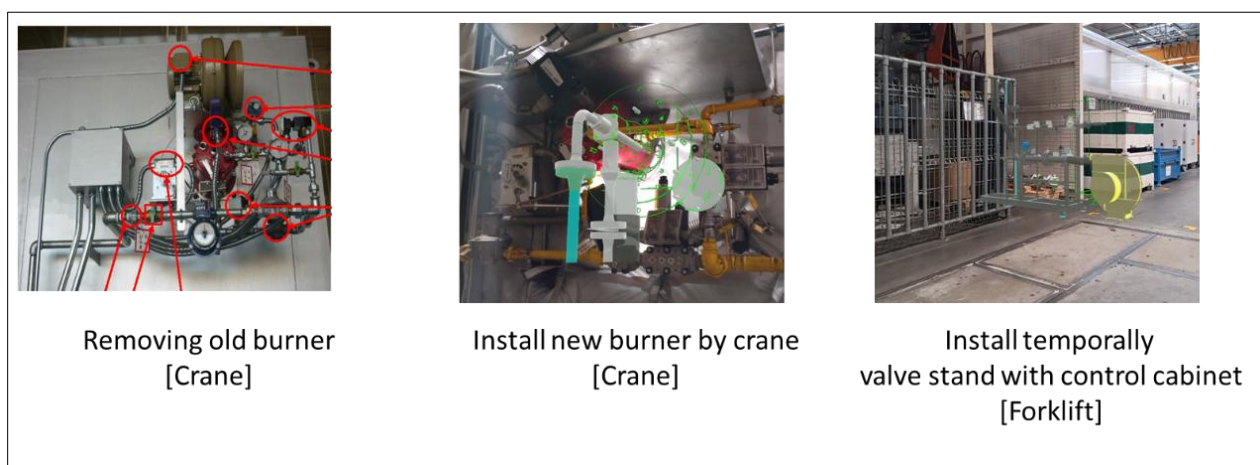


Figure 83: The installation preparation

6.5 Objectives and the demonstration

The primary objectives of the demonstration campaign were:

1. To validate operation of a hydrogen-ready burner in an industrial annealing furnace.
2. To evaluate combustion performance across different hydrogen blending ratios.
3. To assess impacts on furnace temperature control and product quality.
4. To measure changes in emissions, particularly CO₂ and NO_x.
5. To verify the safety and operability of the hydrogen infrastructure under industrial conditions.

The furnace was equipped with a burner capable of operating on both natural gas and hydrogen. The installation included:

- Dedicated hydrogen supply line.
- Existing natural gas supply line.
- Valve train and pressure regulation system.
- PLC-controlled combustion system.
- Air supply equipment.

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- Flexible gas connections to support rapid configuration changes.

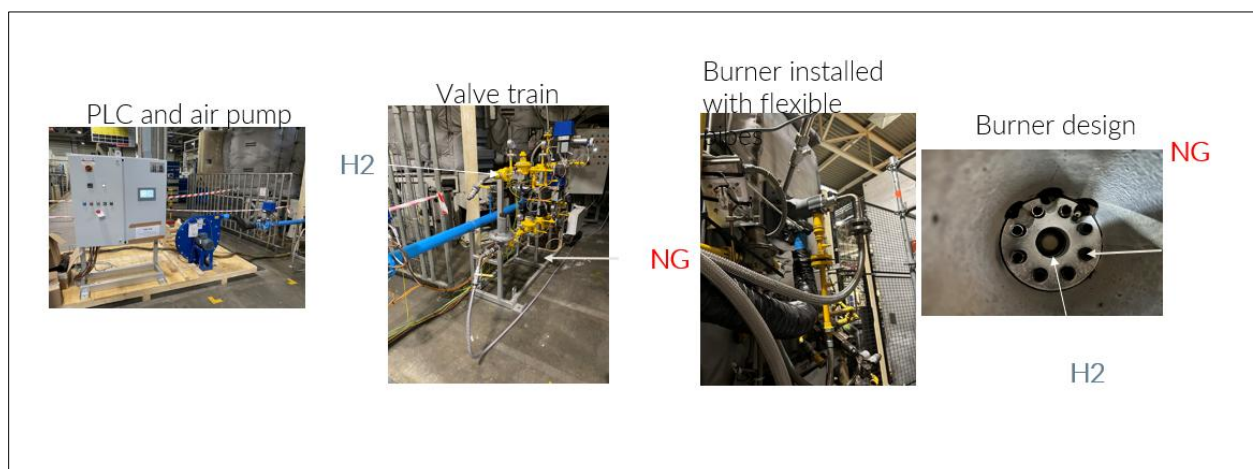


Figure 84: Testing set up

6.6 Process Performance Results

6.6.1 Temperature Performance

One of the primary objectives was to confirm whether hydrogen combustion could achieve the process temperatures required for aluminium heat treatment.

Testing demonstrated that a fuel composition containing approximately 95% hydrogen was capable of achieving a process temperature of around 230°C.

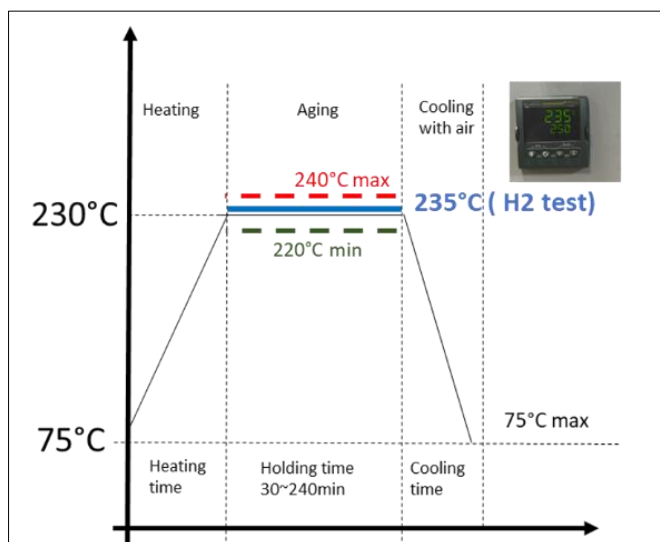


Figure 85: Process temperature

This result confirms that hydrogen combustion can technically support the required thermal process conditions for this application. [\[\]](#)

6.6.2 Operational Challenges

Although the target temperature was achieved, significant challenges were encountered during operation.

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The hydrogen system experienced pressure fluctuations caused by differences in pipe dimensions and gas flow behaviour. During testing, several hydrogen pressure gauges were damaged because of pressure transients occurring when burner demand changed rapidly. Since the actual system pressure could no longer be verified, the trial was stopped for safety reasons.



Figure 86: Flexible piping

This finding highlights that hydrogen retrofits require careful redesign of:

- Pipe diameters.
- Pressure regulation systems.
- Instrumentation selection.
- Dynamic control strategies.

6.7 Environmental results

Two systems were installed to measure the emissions by IOB.

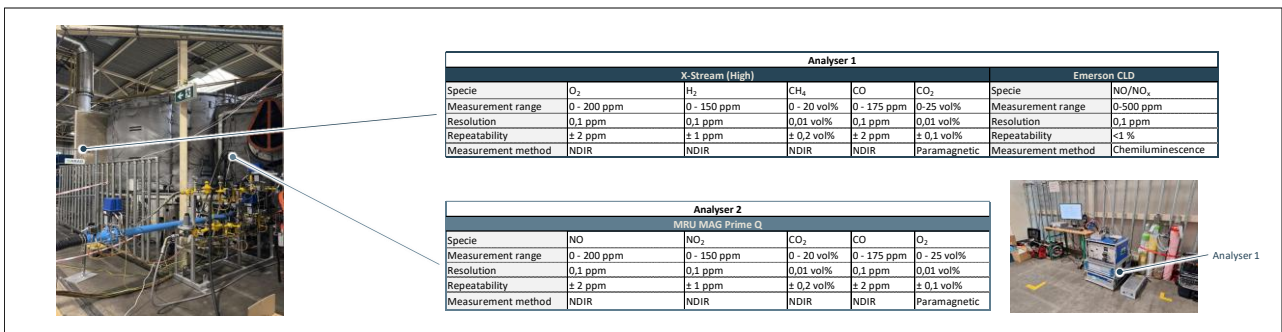


Figure 87: Measurement emission systems by IOB

Unfortunately, due to fluctuation the data was scattered. The analysis of the data were carried out and concluded that the assumed usage of H₂ was predicted 95% hydrogen → approximately 86% CO₂ reduction. Experimental test showed approximately 66% CO₂ reduction which gives only 87% H₂ blend.

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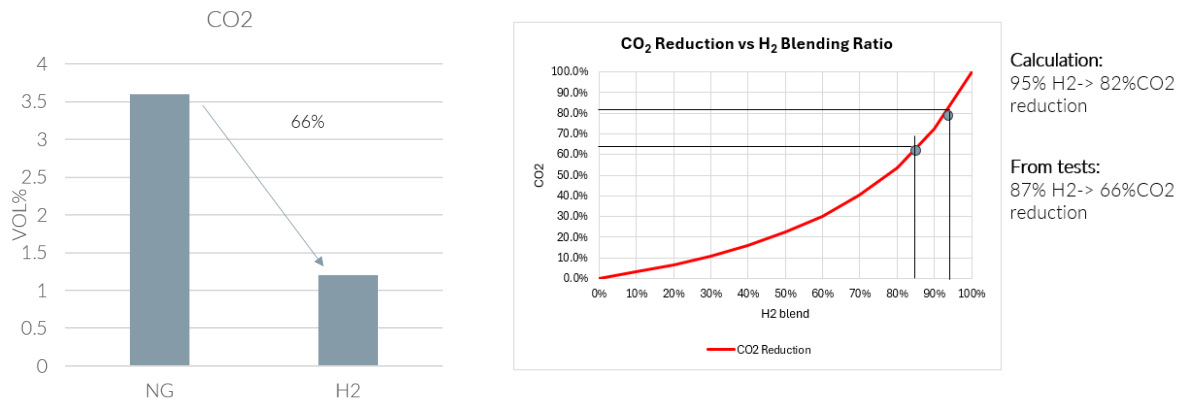


Figure 88: Emission results with the experimental and theoretical calculations

6.8 Computational Fluid Dynamics Simulations

6.8.1 Introduction

A dual-fuel burner fed by two separate mixtures of hydrogen-air and methane-air was simulated in the frame of Large Eddy Simulations (LES). The purpose of the investigation is to analyze how the combustion characteristics at different thermal powers modify the turbulent flame in industrial burner configurations for aluminium industry.

6.8.2 Modelling strategy and numerical description

Simulations were carried out with Alya, the Finite Element Method code developed at CASE Department from BSC to solve multiphysics problems (Vázquez et al, 2016). Calculations have been solved in the frame of Large Eddy Simulations (LES) under the low Mach hypothesis.

To model turbulent combustion the Partially Stirred Reactor (PaSAR) has been applied (Péquin et al., 2022; Rodrigues et al., 2025). In the PaSR each cell is split into a non-reacting and a reacting regions. The ratio between the non-reacting volume and the cell volume is given by

$$\kappa = \frac{\tau_c}{\tau_m + \tau_c}$$

where τ_m and τ_c are the mixing and chemical time scales, respectively. There exist different models to compute them (Péquin et al., 2022). In the current calculations, and following (Rodrigues et al., 2025), these temporal scales are computed as:

- Mixing time scale: based on the deviatoric tensor of the strain rate tensor $\mathbf{S}$:

$$\tau_m = \left(3.24 \nu_t \frac{|\mathbf{S}|^2}{\Delta^2} \right)^{-1/3}$$

where ν_t is the turbulent viscosity (see below for more details) and Δ is the cell size.

- Chemical time scale: it is computed based on chemical time scale associated to the progress variable. The progress variable measures the advancement of the reaction and it is typically defined as a linear combination of species mass fractions with the constraint of being monotonic with the reaction:

$$\tau_c = \frac{\tilde{Y}_c \bar{\rho}}{\bar{\omega}_{Y_c}}, \quad \bar{\omega}_{Y_c} \neq 0$$

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where $\bar{\rho}$ is the density and $\bar{\omega}_{Y_c}$ is the chemical source term for the progress variable. Note: a bar denotes Reynolds filtering while a tilde Favre filtering.

Then each of the filtered mass fractions are computed as a volumetric average of the values at the non-reacting and reacting regions:

$$\tilde{Y}_i = \kappa Y_i^* + (1 - \kappa) Y_i^0$$

being Y_i^0 and Y_i^* the mass fractions of the i-th species at the non-reacting and reacting regions, respectively. Each of them is computed as:

- Y_i^0 is approximated as the mass fraction value at the previous time step.
- Y_i^* is computed after the integration of the chemical system during the LES time step Δt_{LES} at constant pressure, that is:

$$\frac{dY_i^*}{dt} = \frac{\dot{\omega}_i}{\bar{\rho}}$$

with initial conditions $Y_i^*(t = 0) = Y_i^0$.

Regarding the transport equations solved in the CFD, as they are filtered (Large Eddy Simulations), Reynolds stresses are modelled assuming the Boussinesq hypothesis while scalars turbulent transport is described with a gradient hypothesis. The turbulent eddy viscosity (ν_t) is modelled with the Vreman model (Vreman et al., 2004). For the scalars a turbulent diffusivity is obtained dividing the eddy viscosity by a turbulent Schmidt number (set to 0.7). Therefore, the equations to be solved are (after substituting the turbulent transport with previous models):

- Continuity

$$\frac{\partial \bar{\rho}}{\partial t} + \nabla \cdot (\bar{\rho} \tilde{\mathbf{u}}) = 0$$

- Navier-Stokes

$$\frac{\partial (\bar{\rho} \tilde{\mathbf{u}})}{\partial t} + \nabla (\bar{\rho} \tilde{\mathbf{u}} \otimes \tilde{\mathbf{u}}) = -\nabla \bar{p} + \nabla \cdot \boldsymbol{\tau} + \nabla \cdot \boldsymbol{\tau}_{sgs}$$

- Species

$$\frac{\partial (\bar{\rho} \tilde{Y}_i)}{\partial t} + \nabla \cdot (\bar{\rho} \tilde{\mathbf{u}} \tilde{Y}_i) = \nabla \cdot (\bar{\rho} (\tilde{D} + \tilde{D}_{sgs}) \nabla \tilde{Y}_i) + \bar{\omega}_{Y_i}$$

- Enthalpy

$$\frac{\partial (\bar{\rho} \tilde{h})}{\partial t} + \nabla \cdot (\bar{\rho} \tilde{\mathbf{u}} \tilde{h}) = \nabla \cdot (\bar{\rho} (\tilde{\alpha} + \tilde{\alpha}_{sgs}) \nabla \tilde{h})$$

where $\mathbf{u}$ is velocity, p the pressure, $\boldsymbol{\tau}$ the deviatoric stress tensor, $\boldsymbol{\tau}_{sgs}$ the sub-grid stress tensor, h the enthalpy, D the species molecular diffusivity, α the thermal molecular diffusivity while D_{sgs} is the sub-grid species diffusivity and α_{sgs} the sub-grid thermal diffusivity.

Lewis unity number has been considered for all the species. The progress variable is defined as $Y_c = Y_{CO_2}/44.0 + Y_{CO}/28.0 + Y_{H_2O}/18.0$. In this simulation the chemical mechanism from Luca et al. is used (Luca et al., 2018) which consists of 16 species and 73 reactions.

Regarding the solver discretization, spatial discretization is second order while an explicit 3rd order Runge-Kutta scheme in time is used.

6.8.3 Dual fuel burner

The dual-fuel burner consists of a central injection of a premixed hydrogen-air at an equivalence ratio of 0.8 surrounded by eight injectors in an annular configuration of premixed methane-air mixtures also at an equivalence ratio of 0.8. Only adiabatic simulations are considered in the following. Three operating conditions are studied where the thermal power is varied: case A corresponds to a 40% of the maximum flow rate, B to 70% of the nominal value while C to the maximum value. In the following table the Reynolds numbers for each of the pipes and the cases is given:

Table 18: Reynolds number for each of the streams and cases

	Case A	Case B	Case C
Re for CH ₄ -air	2000	3500	5000
Re for H ₂ -air	14000	24400	34800

Simulations have been carried out with Alya with the numerical configuration described above. The mesh consists of 15.5 M of nodes and 87 M of elements composed of tetrahedra and prisms. A representation of the mesh is given in the following figure.

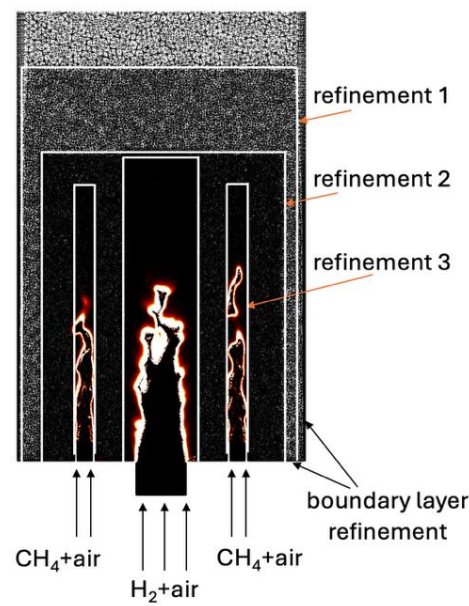


Figure 89: Representation of a slice of the mesh. The field of heat release has been represented to indicate the region where combustion develops. Also the different inlet streams are indicated. The refined regions of the are limited with white lines

As can be observed there exist several refinement regions created to solve a greater range of structures in critical zones, such as the zone where the flame develops, without incurring in an excessive computational cost. A cell size in the order of 0.4-0.5 mm is imposed in the highest refinement regions of the flame (refinement 3). Moreover, an additional refinement close to the walls is defined to improve the resolution of the boundary layer.

Due to the high turbulent Reynolds numbers, and to avoid an excessive computational cost caused by the resolution of the inlet pipes, channel precursor simulations were carried out to provide suitable inlet conditions to the problem. In such channel precursor simulations periodic boundary conditions were imposed at the inlet and outlet. Solutions were temporally tracked on a plane (slice) transversal to the flow and registered in a database. Such database was read cyclically and imposed as boundary condition in the flame simulation.

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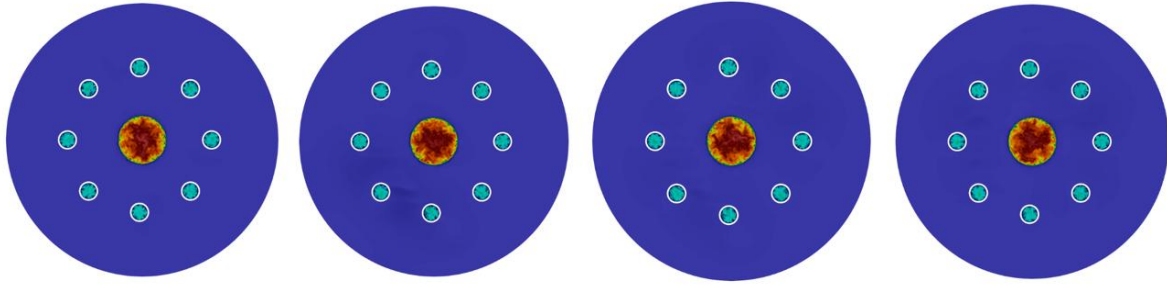


Figure 90: Velocity fields imposed at the inlets of the combustion simulation for four snapshots. Velocity fields are interpolated from the database created from the channel precursor simulations

In first place, the morphology of the flame is studied for the three cases using a temperature iso-surface at 1500 K coloured by heat release. It is evidenced that the increase in thermal power by augmenting the mass flow rates (higher Reynolds numbers) leads to a greater corrugation of the flame due to the enhanced shear stresses, as appreciated from the smaller structures that arise over the temperature isosurface. The hydrogen-air flame systematically shows higher heat release values than the methane-air flame denoting an enhanced reactivity. Also there exists, as expected, an impact on the flame morphology, manifested as well in an increase of the flame length with the inlet velocity.

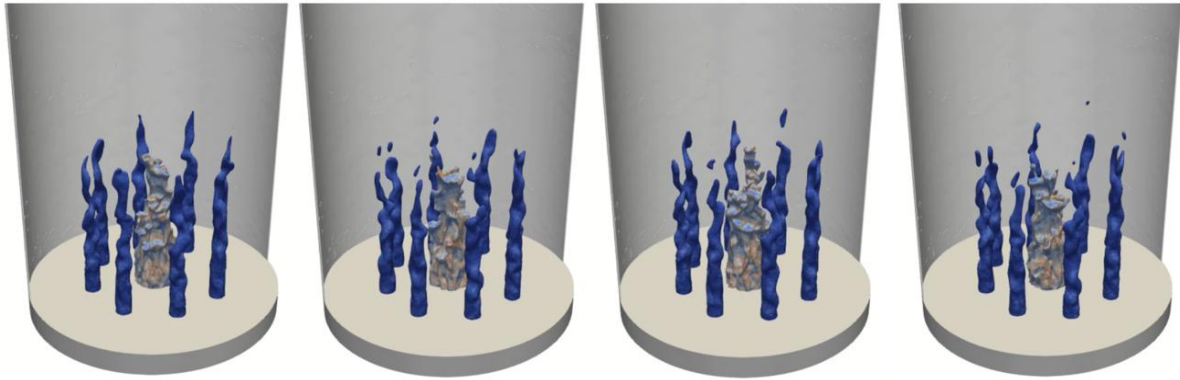


Figure 91: Temperature isosurfaces at 1500 K coloured by heat release for different snapshots for case A

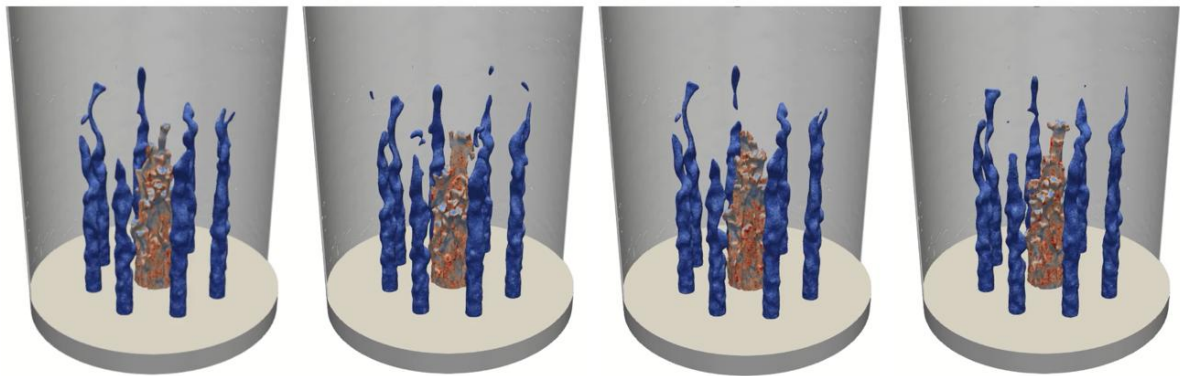


Figure 92: Temperature isosurfaces at 1500 K coloured by heat release for different snapshots for case B

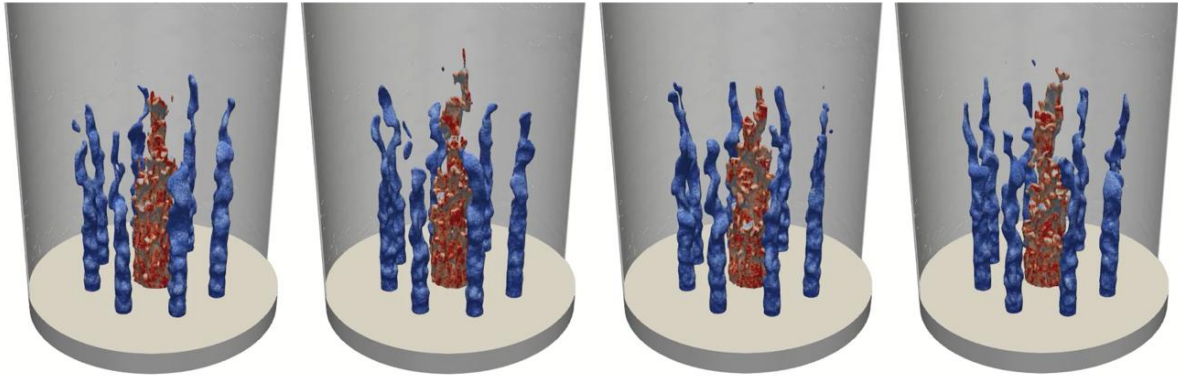


Figure 93: Temperature isosurfaces at 1500 K coloured by heat release for different snapshots for case C

More insights are gained when representing the carbon-based mixture fraction for cases A and C. It is noticed that the flow dynamics are strongly affected by the Reynolds number in terms of the mixture fraction. The increase of the velocities leads to a more complex pattern with a richer content in structures and interaction between both streams, observation that is also appreciated from the wrinkling of the null axial velocity and heat release isolines. However, for both cases the flames mainly develop in regions of homogeneous values of mixture fraction. Moreover, in both conditions there exist reacting mixture pockets detached from the methane-air flame. However, this is not the case for the hydrogen-air stream, which presents a remarkably higher reactivity and then a connected flame front surface.

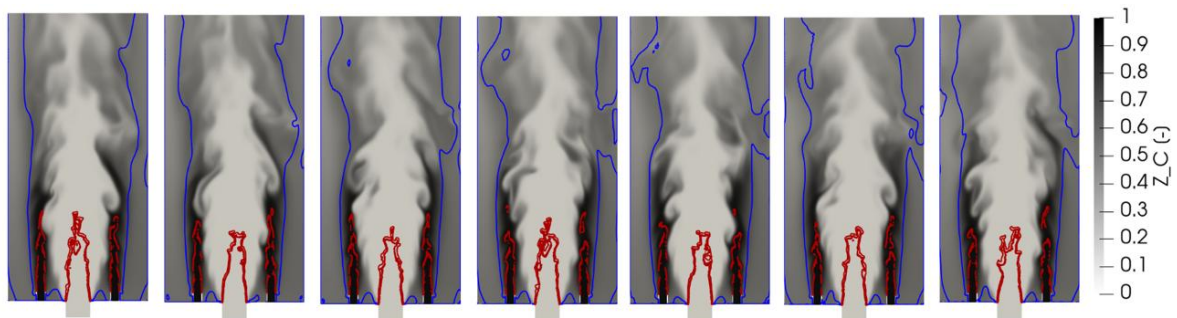


Figure 94: Figure 97: Carbon-based mixture fraction slices for different snapshots for case A. Blue line marks null axial velocity while the red line the heat release isoline for $2 \times 10^8 \text{ W/m}^3$

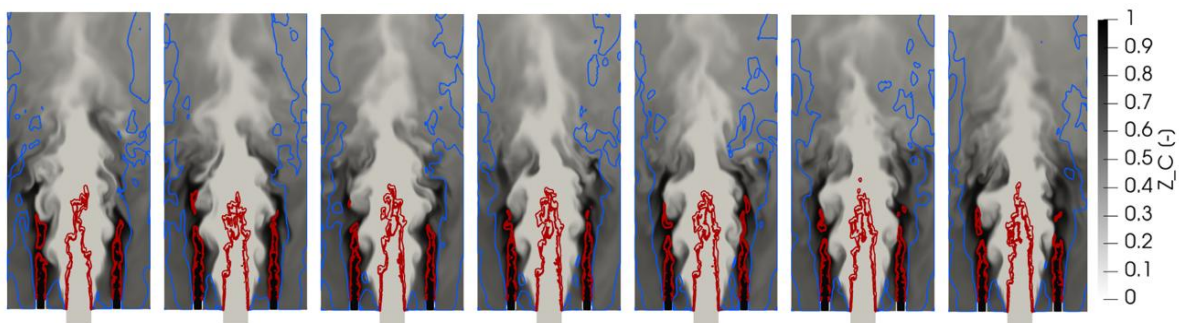


Figure 95: Carbon-based mixture fraction slices for different snapshots for case C. Blue line marks null axial velocity while the red line the heat release isoline for $2 \times 10^8 \text{ W/m}^3$.

The normalized mean axial velocity (normalization with the bulk velocity for H_2 -air stream), represented in the next figure, shows that the increase in velocity displaces the flame length downstream. Such region, marked with a rectangle, presents the highest velocities in the flow due to the thermal expansion. Also there exists a slight reduction of the spreading angle when increasing the Reynolds number.

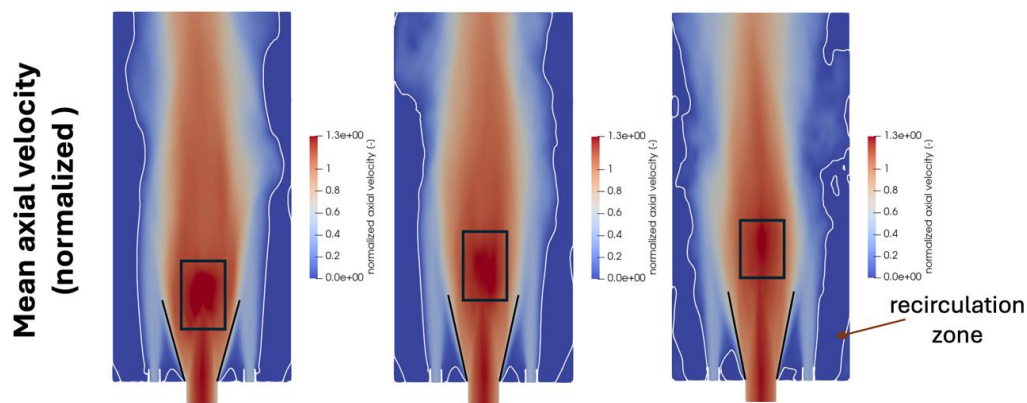


Figure 96: Normalized mean axial velocity for cases A (left), B (centre) and C (right). White line denotes null mean axial velocity. The region of highest velocities produced by the thermal expansion is marked with a rectangle. The spreading angle based on axial

The flame lengths, normalized by the corresponding pipe diameter, are calculated for both streams and gathered in next table. Such length is computed as the maximum distance from the injector for which a threshold of 20% of the maximum heat release associated to each of the streams is reached. While the hydrogen-air flame shows a relationship almost linear with the Reynolds number, in the case of the methane-air flame it saturates to a value of 15.15 diameters approx. for cases B and C.

Table 19: Normalized flame length for each of the streams and cases

	H2+air	CH4+air
Case A	3.34 ± 0.12	12.00 ± 0.31
Case B	4.35 ± 0.28	15.15 ± 0.46
Case C	5.14 ± 0.25	15.19 ± 0.48

6.9 Conclusion

- The TME annealing furnace demonstration represents an important step towards decarbonising industrial heat treatment processes. A great amount of CO₂ reduction has been confirmed.
- The successful integration of a hydrogen-ready burner and dedicated hydrogen infrastructure demonstrated the technical feasibility of retrofitting existing furnaces to operate with hydrogen-natural gas blends and ultimately with 100% hydrogen.
- The project also highlighted the importance of comprehensive safety planning, hydrogen-specific infrastructure design, and ATEX compliance when introducing hydrogen into industrial environments. The knowledge gained from this demonstration will support future large-scale deployment of hydrogen technologies within Toyota and across European manufacturing industries.
- A successful simulation of the dual fuel burner has been carried out.

6.10 References

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7 Laboratory scale melting furnace

7.1 Preamble

This report was originally intended as part of Deliverable 2.1 “Impact of H₂ heating on product quality, yield, and refractory”. Due to delays in the approval process for the required oxygen tank D 2.1 covered only air - hydrogen and air natural gas combustion trials and the oxyfuel trials with a specially designed low temperature oxyfuel burner had to be postponed.

After the introduction a short summary of these cold air trials will be given, since they are the reference for the comparison with the oxyfuel trials.

7.2 Introduction

The attractiveness of using hydrogen for the decarbonization of industrial furnaces stems from the relatively manageable effort required to retrofit existing natural gas-fired installations and continue using them. Due to the expected higher prices of hydrogen in comparison to natural gas, it is necessary to utilize this fuel with maximum efficiency.

When Speira decided to consider hydrogen as a potential path on its decarbonization strategy for its aluminium production it was obvious that combustion of hydrogen should be finally performed with oxygen in place of air, since oxygen can be expected as an available byproduct of the hydrogen electrolysis from water. It is well-known that combustion with pure oxygen achieves significantly higher efficiency in the heating process (Gripenberg, Henrik; Johansson, Anders; Torvanger, Ken, 2012). In the conventional aluminium melting process in gas fired furnaces the exhaust gas contains a considerable amount of water vapor leading to pick up of hydrogen in the melt, which can cause problems in the further production chain, if it is not removed.

It was not clear if a melting process based on 100% hydrogen can keep the hydrogen pick-up in a manageable range. In the same way it was not clear if the characteristics of the oxy-hydrogen flame led to higher metal losses by dross generation and how these effects can be controlled. These questions shaped the motivation for the hydrogen oxyfuel melting tests carried out in Speira's 1t lab scale melting furnace at Speira R&D Bonn.

The following targets are set for these studies:

- Assess the technical feasibility, safety, and environmental benefits of replacing natural gas with hydrogen blends in the laboratory scale furnace.
- Compare the performance of the cold air burner versus the new oxyfuel burner.
- Simulate and validate the laboratory furnace CFD.

7.3 Cold air melting tests

In order to lay a baseline for a comparison, in 2023 melting trials with natural gas and hydrogen were carried out in the same furnace, before the old cold air burner was replaced by an oxyfuel burner. The hydrogen tests in the cold air configuration could be carried out with minor modifications: Essentially, only the burner head with the swirl plate and some valves had to be replaced and the continuous supply of natural gas by pressurized gas cylinders for hydrogen.

The melting tests were carried out with a variety of charge materials to cover the main alloy types in production at Speira and different shapes of feedstocks from ingots over trimmings to compressed bales. The details of these tests can be found in the report D2.1 “Report on how the scale losses, dross formation, and yield of the products and refractories are changed when H₂ burners are used”.

The general conclusion of these cold air tests with natural gas and hydrogen was that within the usual typical scatter of melting trials the differences between both fuels with respect to burner power, specific energy consumption, dross formation and hydrogen pickup were insignificant.

7.4 Installation of Low Temperature OxyFuel (LTOF) burner system

Compared to the cold air tests, the transformation of the furnace for the oxyfuel trials was a major effort and as mentioned in the preamble the approval and installation process lead to significant delays in the project plan. Project partner Linde had designed a special version of its LTOF burners with an integrated pilot burner and two oxygen lances, which fitted into the original mounting of the cold air burner: Due to some inaccuracies of the technical drawings of the furnace housing the original positioning of the burner resulted in a downward-curved flame, which partially flashed back into the burner mounting opening. Supported by numerical modelling the position was corrected, before the commissioning tests of the system started, Details of the applied numerical model can be found in (Garcia-Vergara, Schmitz, Wuppermann, & Buchholz, 2026).

Additional challenges were imposed by the installation of the hydrogen tank, a completely new skid for switching or blending of the main fuel and the replacement and programming of the burner control unit (BCU) by discrete components in place of the former integrated BCU of the cold air burner. The former cold air burner of type Kromschröder BIC140RB used a simple mechanical pressure regulating valve to control the ratio of fuel and comburent. The new oxyfuel burner has more connectors and allows different modes of operation which require careful programming of a microcontroller for the interacting valves. Special care must be applied to program the purging procedures to prevent residuals of explosive gas mixtures in the pipes.

Due to the larger range of flammability of hydrogen compared to natural gas it was decided to run the pilot burner exclusively on natural gas, which increases the safety margin. The correct operation of the flame after ignition is controlled by an ultra-violet sensitive optical probe, which requires a localized flame. By principle this sensor cannot provide a measurement for a distributed flame, which is pursued in order to lower NO_x emissions. For the diluted flame the control system logic must ensure that the ceiling has reached a safe minimum temperature to guarantee auto-ignition of combustible gas mixtures inside the furnace.

Figure 97, Figure 98, Figure 99, Figure 100 show the oxygen tank, stack of hydrogen cylinders, skid and the burner flame before and after the modification of the burner position.



Figure 97: Oxygen tank and evaporator



Figure 98: Hydrogen cylinder rack



Figure 99: Skid for hydrogen and natural gas supply



Figure 100: Flame before correction of burner position

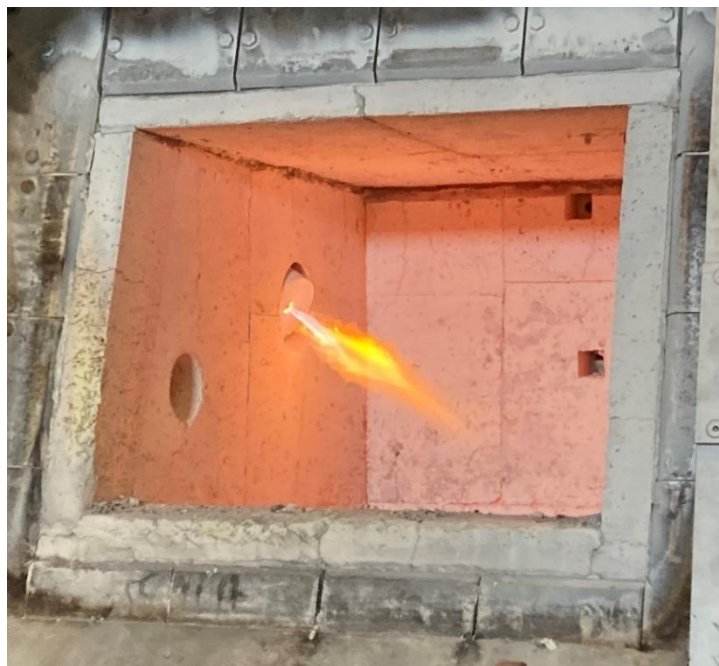


Figure 101: Flame after correction of burner position

7.5 Dry furnace tests

The initial tests were carried out in the dry furnace to verify the correct operation of the burner and to measure the flue gas values in the different operating modes of the burner.

7.5.1 Function and modes of the oxyfuel burner

The burner consists of several pipes which allow for different modes of interaction.

In the very centre of the burner a methane pipe provides the fuel for the ignition burner at 39 mbar, delivering constant power of 20 kW. The required oxygen is supplied by a concentric tube at 300 mbar. The main fuel is fed via an additional concentric duct and providing up to 200 kW of power. The oxygen for the main fuel is provided by two laterally mounted oxygen lances, through which the oxygen can be injected at nearly sonic

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speed requiring up to 5 bar pressure in the ducts. The next figure gives a schematic view of the burner assembly.

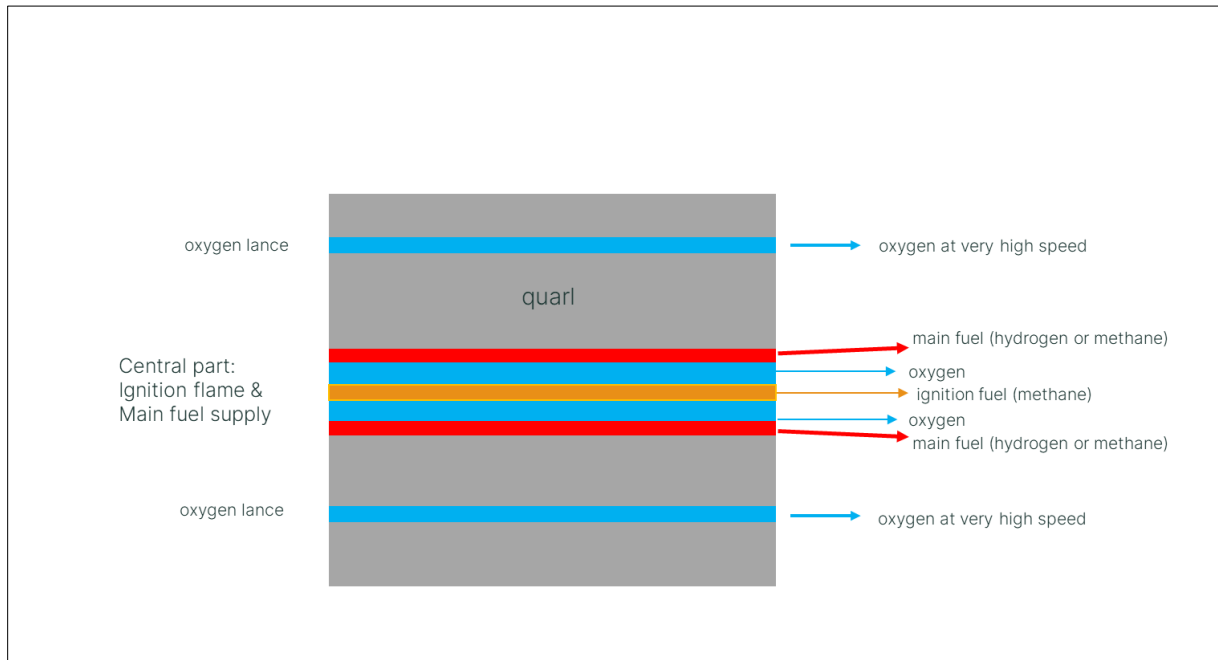


Figure 102: LTOF burner scheme

In combination with the control program this setup provides the following modes of operation:

1. **Ignition mode:** Only the central fuel supply and the central oxygen supply are active.
2. **Normal operation with active pilot burner:** The supply of the main fuel is switched on in addition to the pilot burner and the demand of additional comburent is met by the lateral oxygen lances.
3. **Semi-flameless (SFL) mode:** The fuel supply of the pilot burner is switched off. The central oxygen supply is still active, and the amount of main fuel is increased to maintain the same fuel – oxygen ratio. As a result, there is still a localized reaction zone, which can be supervised by the UV probe. Since the pilot burner is always operated using natural gas, this mode was implemented to facilitate the aluminum heating process without the influence of CO₂.
4. **Flameless (FL) mode:** The central oxygen supply is shut off completely, and comburent is provided solely via the lateral oxygen lances. Due to the high pressure of up to 6 bar the exit velocity of the oxygen is almost sonic. The high momentum is utilized to spread the reaction throughout the entire furnace volume, so that the flame is diluted and cooled by already reacted combustion gases. This measure avoids the critical temperature range for nitrogen oxide (NO_x) formation. In this mode the diluted flame is not visible to the UV probe, so it can no longer be used for flame monitoring. To ensure safe operation, the furnace control only allows this mode to be activated once the ceiling temperature has reached at least 750 °C, ensuring self-ignition of the fuel.

The next figure gives a schematic overview of the possible modes of operation of the LTOF burner.

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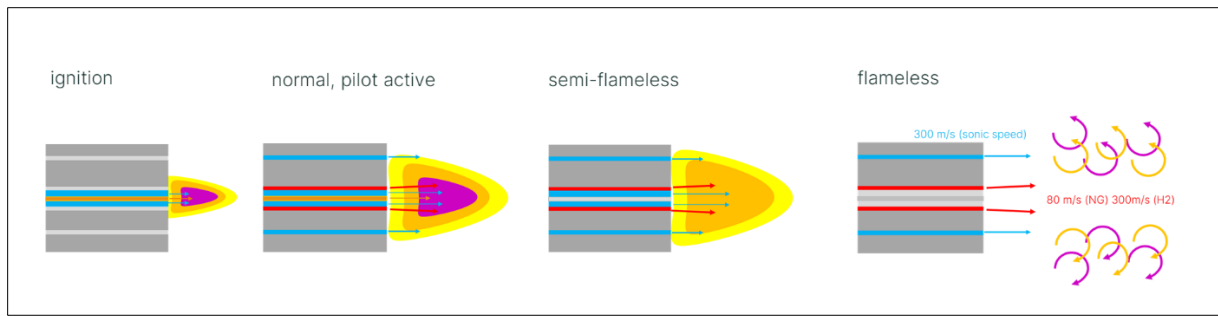


Figure 103: Modes of operation of LTOF burner, light blue: oxygen, orange: natural gas, red: main fuel (natural gas/oxygen)

Before the dry tests started, some initial melting tests revealed comparatively high dross values, when the burner was operated close to its nominal power of 200 kW. Therefore, the operators tended to run the burner at medium power of about 120 kW during the later melting trials.

7.5.2 NOx measurements

The reduced power setting was applied as well in the initial tests to monitor NOx emissions of the new burner system. These tests were carried out in close cooperation with the burner supplier Linde. Linde had prepared special equipment to measure air ingress by doping the exhaust gas with a well-defined volume flow of carbon dioxide (Madhu, et al., 2025). Of course, meaningful air ingress measurements could be carried out only in the semi-flameless and flameless mode, when the natural gas fired ignition burner was switched off. It turned out that the air ingress of the furnace is significant, a factor which had not been considered before. The amount of false air ingress varies depending on the burner output setting and can reach levels of up to 60% of the total flue gas volume). The NOx levels at low power (60 kW) were relatively high.

Surprisingly for the operators, the NOx levels dropped significantly when the burner was operated close to its nominal power. The exact root cause for the air ingress could not yet be identified. Simulation indicates that the pressure drop due to the high gas velocities could play a role. The measurements were carried out with two independent systems (one supplied by Speira, the other by Linde), which had different response times and which account for some of the deviations shown in the tables.

The measured NOx values were set in relation to the applied fuel amount. Especially at low power, i.e. 60 kW, the test delivered very high values of more than 150 mg/MJ for the hydrogen flame in semi-flameless mode and more than 250 mg/MJ in flameless mode. The reference measurements in the cold air burner system in 2023 had shown typical values of 40mg/MJ NO₂ for natural gas at 350 kW and 116 mg/MJ NO₂ for hydrogen combustion at 300 kW.

At high power of 180 kW the situation changed considerably for the LTOF burner: The measurements dropped to values below 10 mg/MJ for hydrogen combustion in flameless mode.

Table 20: Results of NOx measurements at 60 kW for different burner settings

FUEL	NG	NG	Hydrogen	Hydrogen	Hydrogen	NG/H2 50/50 vol.	NG/H2 50/50 pow.	NG
MODE	Pilot	Flameless	Pilot	Semi-flameless	Flameless	Flameless	Flameless	Flameless
Time	09:28	10:03	10:12	10:26	10:52	11:00	11:07	11:13
NG pilot (Nm ³ /h)	1.9	-	1.9	-	-	-	-	-
O ₂ center (Nm ³ /h)	4.06	-	4	4	-	-	-	-
NG (Nm ³ /h)	3.8	5.7	-	-	-	4.45	2.9	5.7
H ₂ (Nm ³ /h)	-	-	13.3	20	20	4.45	9.8	-
O ₂ lance (Nm ³ /h)	7.98	12	7	6.5	10.5	11.7	11.3	12
O ₂ dry (vol. %)	18.9	16.9	19.9	23.6	21.2	12.9	16.7	16.7
CO ₂ (vol. %)	19.2	19.2	8.5	0.3	0.2	18	12	20
NOx Linde (ppm)	1188	369	1176	1629	369	237	205	252
NOx Linde (mg/MJ)	332.8	115.6	377	163.4	111	86.5	64.9	76
NOx Speira (ppm)	1071	257	1438	2081	287	84	132	232
NOx Speira (mg/MJ)	300	80.5	461	208.7	86.36	30.67	41.8	70
Air flow (Nm ³ /h)	21.5	24.9	29.58	10	31.1	31.9	28.8	23.8
total gas volume (Nm ³ /h)	39.24	42.6	55.78	40.5	61.6	52.5	52.8	41.5
fraction air ingress	55%	58%	53%	25%	50%	61%	55%	57%

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Table 21: Results of NOx measurements at 180 kW for different burner settings

FUEL	NG	Hydrogen	Hydrogen	Hydrogen	NG
MODE	Flameless	Flameless	Pilot	Semi-flameless	Pilot
Time	11:20	13:20	13:24	13:48	14:04
NG pilot (Nm ³ /h)	-	-	1.9	-	1.9
O ₂ center (Nm ³ /h)	-	-	4	4	4
NG (Nm ³ /h)	17.1	-	-	-	15.3
H ₂ (Nm ³ /h)	-	59.8	53.4	59.8	-
O ₂ lance (Nm ³ /h)	36.7	31.5	28	28	32
O ₂ dry (vol. %)	5.65	35	30.6	40.6	10.6
CO ₂ (vol. %)	77.6	1	20.4	0.8	72.8
NOx Linde (ppm)	142	161	317	561	476
NOx Linde (mg/MJ)	11.7	4.1	8.8	13.9	37.2
NOx Speira (ppm)	29	137	347	535	296
Nox Speira (mg/MJ)	2.4	3.5	9.6	13.3	23.1
Air flow (Nm ³ /h)	4.9	6.4	5.3	5.7	4.7
gas volume(Nm3/h)	58.7	97.7	92.6	97.5	57.9
fraction air ingress	8%	7%	6%	6%	8%

7.6 Melting trials

For the melting trials different charge materials were selected, which represent typical alloys produced in Speira's factories and different degrees of chunkiness. The intention was to use similar materials as in the cold air trials in 2023. As a precaution it must be stated that it is almost impossible to provide identical charge material. Material that is stored for a period of more than one year is subject to various aging mechanisms that may affect melting behaviour and oxidation.

The following feedstock was used:

- Ingots
- Can body stock (CBS, alloy 3xxx)
- AlMg5 edge trimmings (alloy 5182)
- Edge trimmings of foil production
- Bales of foil production scrap

CBS was supplied as baled scrap. Trimmings are the cut off edges from the rolling process to maintain a controlled edge shape. Edge trim scrap usually contains small residues of rolling oil.

The melting followed the same procedure as applied in the cold air trials: In each charge about 400 – 500 kg of feedstock were put into the preheated main chamber and heated until all material was molten. The amount of fuel consumed between charging the metal and reaching a bath temperature of 730 °C forms the basis for calculating the specific energy consumption. The melting rate is derived from the corresponding time interval. At the end of the melting process, the dross was manually skimmed off the surface of the melt using a rake and then weighed. The next series of figures show the furnace with various charge materials and at different stages of the melting process.



Figure 104: Typical edges trimmings used as feedstock



Figure 105: Loaded furnace with pilot flame switched on



Figure 106: Burner flame switching to normal mode



Figure 107: Melting of ingots



Figure 108: Preheated furnace fully charged with trimmings

The previously mentioned formation of a hotspot becomes apparent on the right side of the furnace, which necessitated operating the burner at reduced power.



Figure 109: Hot spot formation at right wall



Figure 110: All metal has melted; the bath thermocouple is immersed in the melt at the rear right



Figure 111: Manual skimming of dross.

7.6.1 Specific energy consumption

The right part of the next **Fehler! Verweisquelle konnte nicht gefunden werden.** shows the values of specific energy consumption for different types of charge material for natural gas and hydrogen for normal and flameless operation of the LTOF burner. These results can be compared with the equivalent measurements from 2023 on the left half of the figure,

It is obvious that oxyfuel combustion requires significantly less fuel than the original cold air burner system. The difference between the burner types is much more prominent than the difference between natural gas and hydrogen as fuel. On average, the fuel consumption is approximately 50% lower than that of the cold air burner.

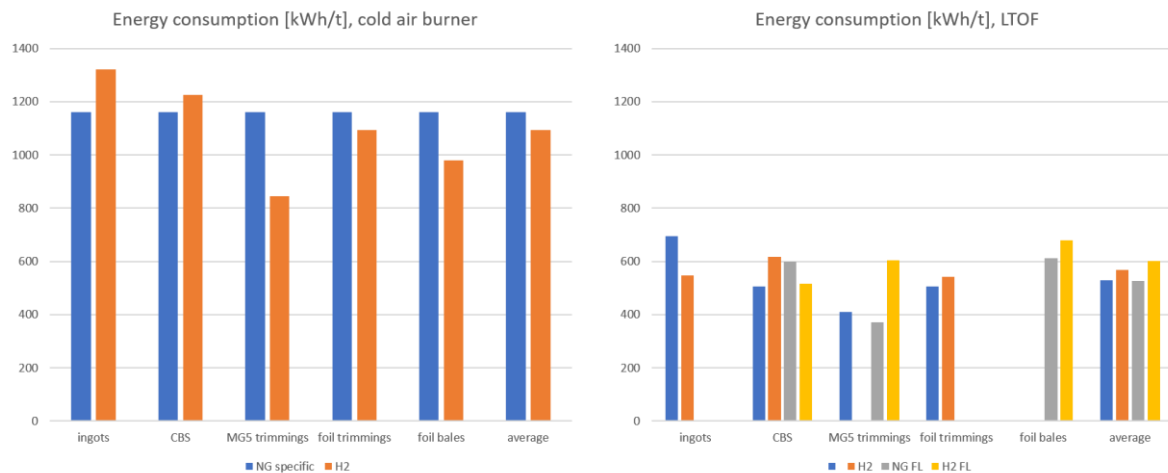


Figure 112: Specific energy consumption for different types of charge material. Cold air burner versus LTOF burner results

7.6.2 Melting rate

As mentioned earlier, due to the observed hot spot problem on the right side of the furnace chamber the melting trials had to be performed with lower burner power than originally intended. In general, this led to a significant reduction of the melting rate in comparison to the cold air burner trials. While the cold air burner system usually achieved the nominal melting rate of 200 kg/h the results for the LTOF burner averaged around 150 kg/h. However, for lumpy feed material (ingots) there were indeed positive deviations upward, indicating that higher melting rates should in principle be achievable.

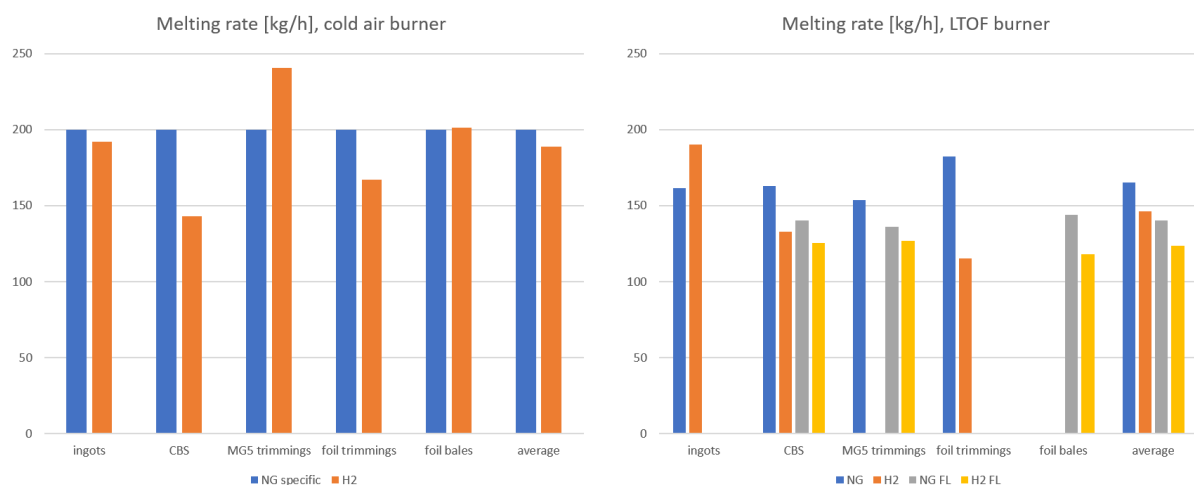


Figure 113: Comparison of melting rates for cold air and oxyfuel combustion for different charge materials and fuels

7.6.3 Dross generation

The hotspot issue mentioned earlier becomes particularly evident when evaluating the amount of dross generated. It should be noted that the term “dross” here does not refer to oxidized metal, but rather to the mixture consisting of oxides, adherent melt residues and gas bubbles that rises to the surface of the melt and is skimmed off with a rake. The amount of dross skimmed off is related to the amount of feed material and forms the basis for the representation shown in the next **Fehler! Verweisquelle konnte nicht gefunden werden..** Nearly for every feedstock, at least a doubling of the dross quantities compared to the cold-air burner can be observed. While values above 20% are concerning, there are positive exceptions, particularly for coarse or very clean feed materials.

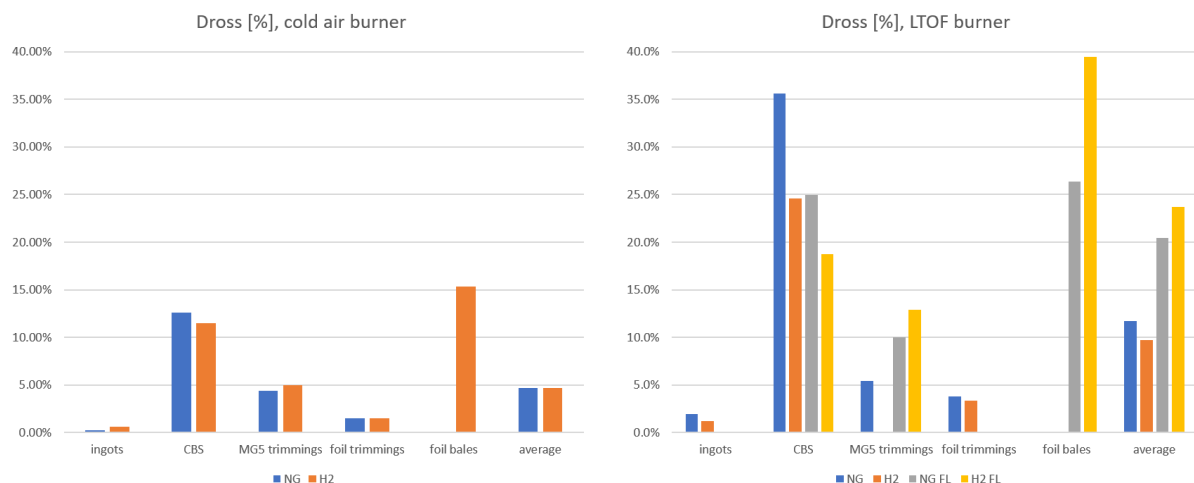


Figure 114: Dross generation, cold air burner(right) versus LTOF (left)

7.7 Hydrogen pickup measurements

To monitor the pickup of hydrogen the furnace is operated in multi-chamber mode. In this configuration two holes in the main chamber are opened to connect it to the external chamber which is separated into two connected compartments. One contains a mechanical circulation pump, the other two ALSCAN devices (ABB, 2026) to sample the hydrogen content of the melt. The melt is drawn into the pump chamber and then passes through an opening in the partition wall into the sampling chamber, where the hydrogen concentration is continuously monitored by two probes as shown on the next figures. It then flows back into the main chamber, where the burner keeps the melt at a constant temperature. In these tests the furnace was run in holding mode, i.e. no metal was melted, it was only kept at temperature. The burner power was reduced to compensate for the heat losses in order to keep stationary temperatures for several hours, while the melt was circulating. Hydrogen sampling was carried out in Al99.5 at 800°C and 750°C and in AlMg5 only at 750°C due to very high dross formation at 800°C, which disturbed the measurements.

The hydrogen content in Al99.5 was about 0.9 ml/100g at 800°C both in natural gas and hydrogen combustion. At 750°C this dropped to a level of 0.55 ml/100g for both fuels. In Al99.5 there was virtually no difference in hydrogen uptake between natural gas and hydrogen as fuel. This changed in the high Mg melt at 750°C: Natural gas combustion yielded a hydrogen level of 0.58 ml/100g and hydrogen as fuel only value of 0.3 ml/100g. It is likely that the brittle oxide skin in an MG rich alloy promotes the diffusion of hydrogen. This can lead to a faster pickup of hydrogen, but also to a faster release once the partial pressure of water vapor in the environment drops significantly. Under the flow conditions of the three-chamber mode of the furnace it seems that the escape of hydrogen dominates over the pickup compared to an Al99.5 melt.

These oxy-fuel experiments must be compared with the results obtained from cold air combustion: In the cold air combustion trials the hydrogen content in Al99.5 melt was about 0.6 ml/100g at 800°C and 0.5 ml/100mg at 750° showing virtually no difference between natural gas and hydrogen as fuel. The measurements in AlMg5 melt at 750°C showed levels of 0.53 ml/100g for natural gas and 0.42 ml/100g for hydrogen. Again, the brittle oxide skin seems to foster the escape of hydrogen compared to the Al99.5 melt.

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In conclusion, it can be stated that within the technically relevant temperature range at 750 °C, hydrogen uptake differs only marginally between oxy-fuel and cold air combustion, as well as between the two fuels, hydrogen and natural gas.



Figure 115: Setup for hydrogen pickup measurements: external chamber divided into a pump (right) and into a sampling chamber (left)



Figure 116: AISCAN probes before (left) and after use (right)

7.8 Retrospective analysis

Although the tests showed that under optimal conditions the oxyfuel burner achieves the expected efficiency, the observed hotspot problem called for a solution. In principle, distributed combustion should mitigate the problem of overheating the melt, and indeed the favourable results of the nitrogen oxide measurements indicate that the mechanism of diluted combustion is fundamentally functioning as expected. For this reason, the results of the numerical simulations were examined for additional indicators of possible issues.

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It became apparent that the temperature distribution in the furnace alone cannot account for the observed increased oxidation of the melt, since the temperatures in the furnace chamber for the LTOF burner and the cold air burner are quite comparable. However, it is noticeable that the wall shear stresses of the gas flow in the LTOF burner are significantly higher in the region where hotspots form, despite the overall gas volume flow being considerably lower.

To mitigate this issue, comparative simulations were carried out with modified burner orientations that could be implemented in the existing furnace. These showed that a simple horizontal alignment of the burner should lead to a substantial reduction in wall shear rates, even to levels below those of the cold air burner. Although a corresponding modification of the furnace was considered, it could not be implemented within the HyInHeat project due to time constraints and limited furnace availability.

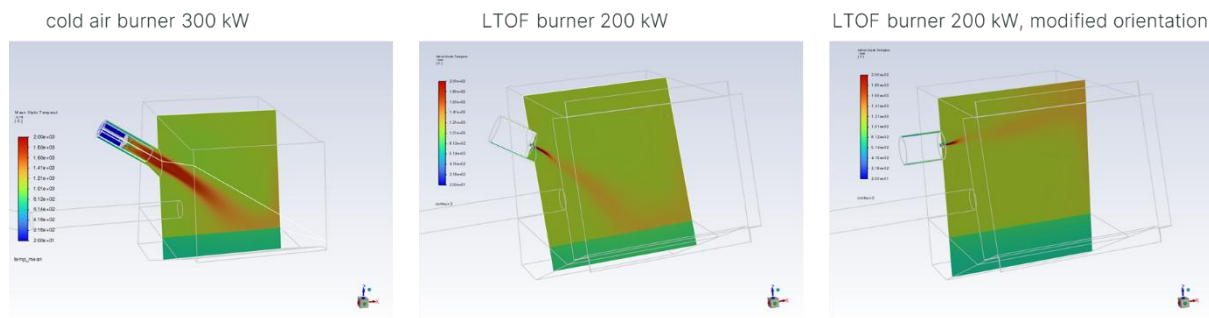


Figure 117: Impact of burner orientation on thermal fields for cold air burner, LTOF burner and realigned LTOF burner

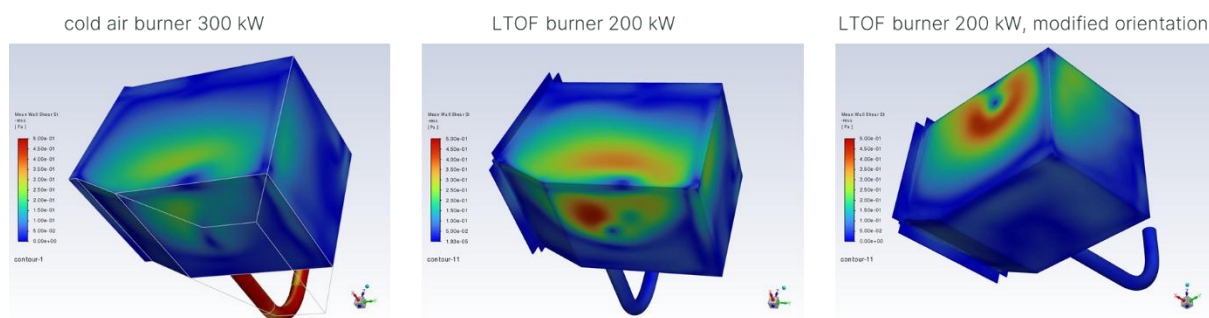


Figure 118: Wall shear stress exerted by gas flow on wall and melt surface for burner configurations

7.9 CFD simulation of the lab-scale melting furnace

Speira's R&D facility uses a 1.5-ton melting furnace to perform melting trials, positioned between lab-scale experiments and small production units. In its basic configuration, the furnace consists of a heating (main) chamber equipped with a 350-kW cold air burner. The control system of the furnace regulates the burner's power according to thermocouples located in the melt, the ceiling, and the oxygen in the flue gas. The next figure shows pictures of the furnace and the inside of the heating chamber with the door open. The furnace also includes an external chamber with two connections to the heating chamber that can be modified to establish a melt circulation system for investigating different types of melt treatment and measurements of melt quality.

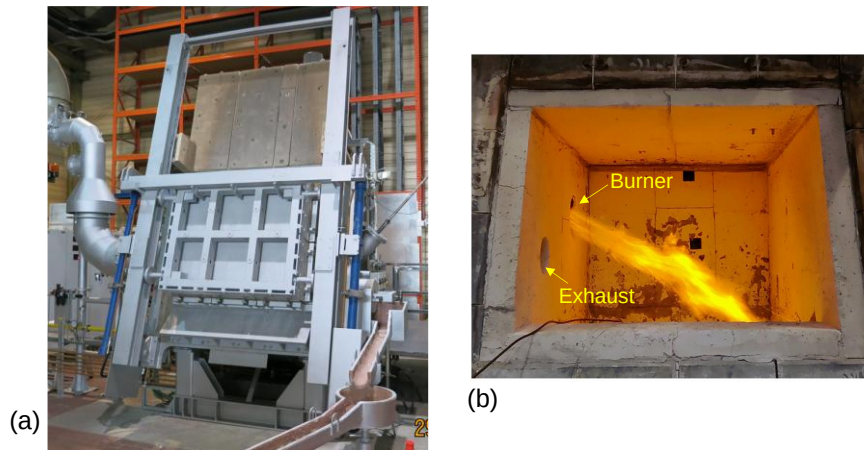


Figure 119: View of the (a) lab-scale melting furnace and (b) inside of the heating chamber

The furnace is originally designed to operate with natural gas using a cold air burner of the type Honeywell Kromschröder BIC 140R-450/485/47 with a nominal power of 350 kW. To operate with hydrogen as fuel, the burner head of type RB47 is exchanged for a head of type HD65, which is designed for pure hydrogen combustion. Although a gradual transition from natural gas to hydrogen is sometimes desired, the transition to pure hydrogen was chosen. A schematic of the two types of burner heads is presented in the next figure.

The head for hydrogen combustion differs in both the air and fuel injection paths. For the air path, the angle of the swirler blades is reduced from 45° to 15°, and the diameter of the 12 axial holes is increased from 6 to 11 mm. The fuel injection changed from 10 radial holes with a 5 mm diameter to 12 radial holes with a 3.5 mm diameter and 6 additional axial holes with a 6.7 mm diameter. Due to this modification, the fuel and air are injected with a higher axial momentum, preventing the burner from overheating due to a proximity of the flame to the burner head.

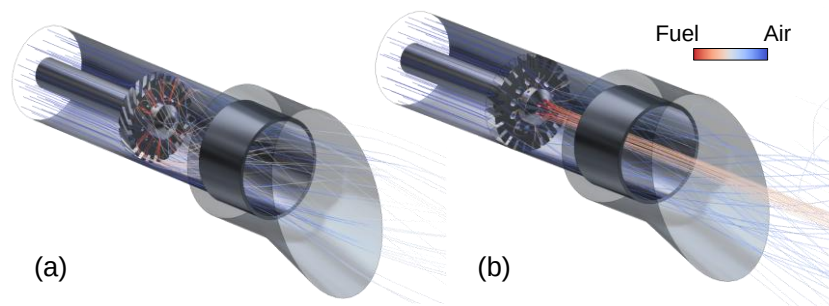


Figure 120: Cold air burner Honeywell-Kromschöder with head (a) RB47 for methane and (b) HD65 for hydrogen

7.10 Low-temperature oxyfuel burner

Within the scope of the HYINHEAT project, the retrofitting of Speira's aluminium melting furnaces is evaluated with the aim of reducing fuel consumption and environmental emissions. To achieve this, the lab-scale furnace will be equipped with a new burner designed for hydrogen-oxyfuel combustion, and the impact on the furnace performance and melt quality will be analyzed. A low temperature oxyfuel (LTOF) burner for hydrogen is designed by Linde.

In conventional oxyfuel burners, air is replaced by pure oxygen in the combustion process, offering several advantages. The total amount of flue gases is reduced, as the large fraction of nitrogen in air does not participate in the heating process. As a result, the temperature of the flue gases increases, enhancing the efficiency of heat transfer by both radiation and conduction. The concentrations of radiatively participating species in the combustion gases—such as water vapor and carbon dioxide—also increase, further improving heat distribution inside the furnace. Additionally, the reduced gas volume significantly lowers heat losses through the off-gas for a given operating temperature. Overall, these factors lead to more efficient utilization of the fuel's energy.

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On the other hand, the high flame temperature of conventional oxyfuel burners poses the risk of overheating the charge material or the refractory lining and may also lead to NO_x formation due to air leakage. To overcome these disadvantages, MILD (Moderate or Intense Low Oxygen Dilution) combustion [1,2], or flameless oxidation, is applied in the Low Temperature Oxyfuel (LTOF) burners developed by Linde. In these burners, the high momentum of the injected oxygen induces strong flue gas recirculation and intense mixing within the furnace, which spreads and dilutes the fuel and oxygen, slowing down the chemical reactions and distributing the reaction zone over a wide volume, as illustrated in the next figure. Additionally, recirculation of reaction products into the reaction zone cools the flame and prevents the formation of a pronounced hot flame core.

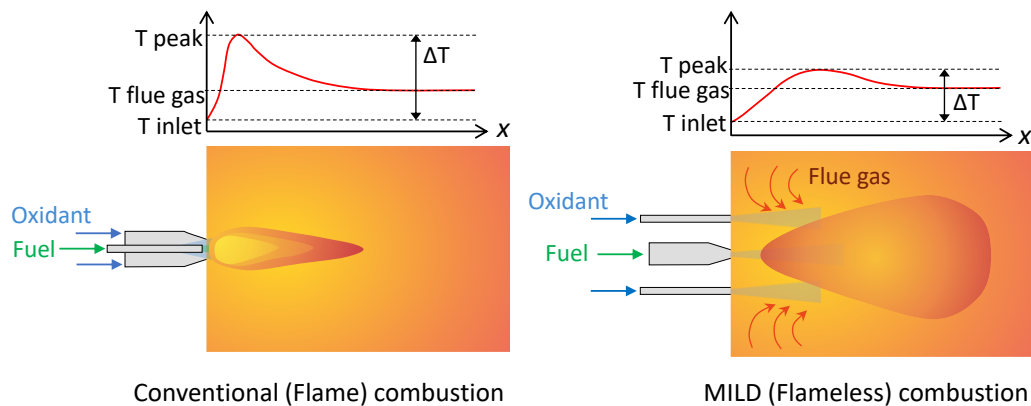


Figure 121: Schematic of the MILD combustion concept for the Low Temperature Oxyfuel burners

A schematic of the burner concept is presented in the next figure. The hydrogen and oxygen are injected axially in separate streams. The fuel is injected into the central region of the burner, while the oxygen is injected through two lances at high speed to induce flue gas recirculation, resulting in low-temperature combustion similar to the MILD combustion regime [3]. The burner also features a secondary injection system for fuel (hydrogen or methane) and oxygen at the center, functioning as a pilot for ignition. The pilot can be deactivated once the furnace temperature is sufficient to sustain MILD combustion. However, the oxygen flow to the pilot may be maintained during transient conditions or door openings, when the recirculated flue gases are not hot enough to support stable combustion. After ignition, the pilot oxygen flow is regulated to constitute 10–20% of the total burner oxygen flow, helping to maintain combustion stability without compromising overall performance.

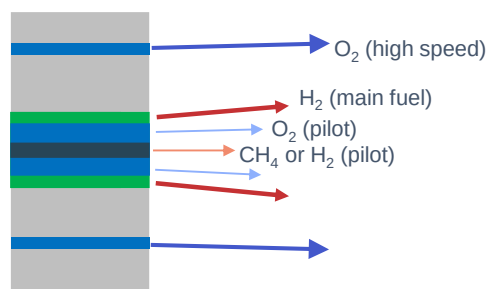


Figure 122: Schematic of the fuel and oxygen injection concept for the LTOF burner designed by Linde

Computational fluid dynamics (CFD) simulations are conducted to evaluate the impact of the low temperature oxyfuel burner on the performance of Speira's lab-scale furnace compared to air combustion with both natural gas and hydrogen.

7.11 Numerical model

The lab-scale furnace normally operates in batch mode as a transient heating/melting process, with the thermal power regulated based on the operating temperature measured at the furnace ceiling. For the CFD work, which focuses on the impact of the new burner technology on thermal efficiency, the furnace is modeled in a steady state, replacing the heating/melting process with a thermal load located 30 cm above the furnace bottom, corresponding to the level of the molten aluminum when around 610 kg is charged. The mesh and computational domain are illustrated in the next figure (a). The furnace interior is 120 cm wide and has a height of 150 cm from the bottom to the ceiling. The computational domain is discretized with a non-structural mesh made of polyhedral elements with a four-element prism layer at the wall surfaces. Approximately 0.86 million elements are used for the air combustion burners, while around 1.2 million elements are used for the oxyfuel combustion burner. Various refinement levels are utilized in the burner zone, as shown in the next figure (b), to improve the prediction of the injection, mixing, and combustion process.

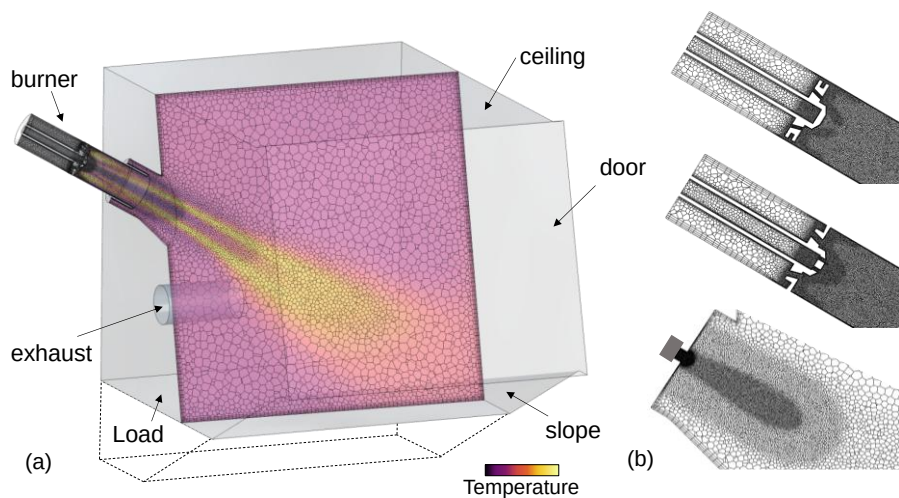


Figure 123: (a) View of the computational domain of the lab-scaled furnace and (b) detail of the mesh at the burner for CH₄-air, H₂-air, and LTOF from top to bottom

The lab-scale furnace is modeled using the Reynolds Averaged Navier-Stokes (RANS) approach, employing a double-precision solver based on pressure in the commercial software ANSYS – Fluent 2023 R1. The pseudo-time stepping scheme was used for the pressure-velocity coupling, and pressure interpolation was managed by the PRESTO! algorithm [4]. The Second-Order Upwind special discretization scheme is used for all the transport equations.

The Reynolds stress tensor in the RANS transport equations was calculated based on the Boussinesq hypothesis using the κ - ω SST (Shear Stress Transport) turbulence model [5]. This model combines the κ - ω model in the near-wall region with the κ - ϵ model in the freestream, enhancing predictions of flow separation and adverse pressure gradients. It employs a blending function to transition between the κ - ω model near the wall and the κ - ϵ model in the outer region. The ideal gas law is used to calculate density, assuming incompressible flow for the air combustion burners. However, for the LTOF burner, the flow is considered compressible due to the high speed of the oxygen injection.

The Discrete Ordinates Model (DOM) [6] is used to solve the radiation heat transfer equation (RTE) with an angular discretization of 4×4 , considering diffuse radiation and neglecting scattering. The gas radiation was calculated based on the weighted-sum-of-gray-gases (WSGG) model [7], but only one RTE was solved instead of multiple RTEs for each of the gray gases. This means an effective gas absorption coefficient was calculated as a function of the temperature and species composition. The WSGG model designed in task 1.4 for mixtures ranging from pure methane to pure hydrogen is used combustion [8]. Two models of the WSGG model are

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calibrated: one for air combustion and one for oxyfuel combustion. Wall emissivity is set to 0.6 for the furnace and 0.7 for the burner.

7.11.1 Combustion model

Hydrogen and oxyfuel combustion pose a challenge for the combustion model developed for RANS CFD simulations. Therefore, new models are being developed and assessed in Task 2.3, and the results will be presented in deliverable D2.3, “Report on simulation framework for H₂/O₂ and H₂/air combustion.” For the current analysis, the combustion modeling is based on the Eddy Dissipation Concept (EDC) model [9], due to its capability to model various combustion regimes. A comparison of the results with the Flamelet Generated Manifold (FGM) model [10] is also performed.

The EDC model considers species transport by solving N-1 transport equations for the N species involved in the combustion process. Each equation has a production/consumption term for the species, calculated from the chemical kinetics describing the oxidation of the fuel. The EDC describes the chemical-turbulence interaction by assuming that reactions occur in small turbulent structures. It expresses the mass fraction of these fine structures and the mean residence time of the fluid within them as a function of the flow characteristic scales [11,12]. Combustion in these structures is assumed to occur as a constant-pressure reactor, where the initial conditions correspond to the temperature and concentration in the cell. The Arrhenius equation describes the reaction rates over the structure mean residence time, and these are numerically integrated using an ODE solver with the ISAT algorithm [13] to reduce computational time.

The oxidation of the fuel in the three burners is described by the kinetic mechanism DRM19 [14], which includes 19 species and 84 reactions. This is a reduced form of the detailed GRI 2.11 mechanism, a previous version of the widely used GRI 3.0 [15]. GRI 3.0 accurately describes the kinetics of mixtures ranging from pure methane to pure hydrogen [16,17] and oxygen enrichment of methane [18]. The DRM19 mechanism retains close accuracy while offering lower computational cost due to the fewer species considered.

The computational cost associated with solving 19 species transport equations is still high for applications involving full-scale furnace modeling or when low computational power is available. One option to reduce computational costs is to use a global mechanism (GM), an empirical scheme that considers only the major species involved in the combustion process, described now by a reduced number of global reaction steps. These mechanisms are calibrated to match key physical properties of the flame, such as laminar flame speed, auto-ignition delay time, or species production rates. The next series of figures compares the laminar flame speed and the adiabatic flame temperature computed with GRI 3.0, DRM19, and GM with four steps for the case of methane and one step for the case of hydrogen [19]. Although the flame speed is well reproduced in the case of air combustion, the flame temperature is overpredicted due to the lack of intermediate species. This results in a significant error for oxyfuel combustion.

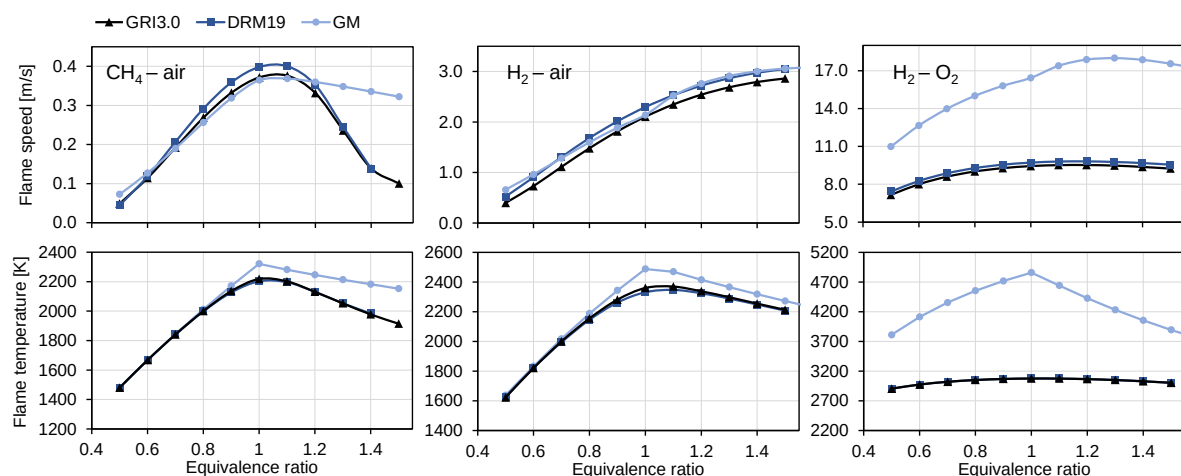


Figure 124: Unstretched laminar flame speed and adiabatic flame temperature with detailed, reduced, and global reaction mechanisms

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A different approach to reducing the computational cost of CFD simulations of reacting flows is to use combustion models based on chemistry tabulation. In this approach, the thermochemistry is processed and tabulated before the simulation and then accessed based on a reduced number of control variables transported in the CFD. Therefore, only a few additional transport equations are solved instead of $N-1$ when the species are transported.

The main model in this category is the Flamelet Generated Manifold (FGM) model [10,20]. This model assumes that a turbulent flame can be considered as an ensemble of one-dimensional laminar flames (flamelets), which are used to construct a manifold parameterized based on the mixture fraction, the progress variable, and the enthalpy (heat loss/gain). The mixture fraction describes the fuel-oxidant mixing, while the progress variable describes the combustion process from the unburnt reactants to the burnt products. The source term in the transport equation of the progress variable is also computed with the flamelets and store in the manifold.

The turbulent-chemistry interaction is considered by integrating the laminar manifold with a β -shape probability density function (PDF) [20], considering statistical independence between the mixture fraction and the progress variable. The resulting PDF is tabulated such as the thermochemistry states (temperature, species mass fraction, and gas properties) are described by the enthalpy and four control variables: the mixture fraction, the progress variable, and their variances.

A 1D freely propagating premixed flame is used to compute the flamelets at various mixture fractions, ranging from the lower flammability limit to the upper flammability limit, and then extrapolated up to pure oxidant and pure fuel. In the current case, the manifold is built with 40 points in the mixture fraction space and 80 points in the progress variable space. The process is repeated with non-adiabatic flamelets to consider the effect of heat loss and gain on the chemistry, using 21 points for enthalpy space. Finally, the PDF is built with 15 points in both mixture fraction variance and progress variable variance. The progress variable is defined based on the species mass fraction as $Y_c = Y_{CO} + Y_{CO_2} + Y_{H_2O}$ for methane combustion and $Y_c = Y_{H_2O} + 10Y_{HO_2}$ for hydrogen combustion [4].

The standard FGM model is based on the unity Lewis assumption (species mass diffusion equal to thermal diffusion) for the computation of the flamelets and the derivation of the control variable transport equations. This assumption is not realistic for hydrogen combustion necessitating revised models for accurate flame behavior predictions. This is the goal of Task 2.3; hence the standard version is evaluated here.

Although one of advantages of the FGM model is to allow using detailed mechanisms without additional computational cost of the CFD simulation, the DRM19 reduced mechanism is used to compute the flamelets in order to have a direct comparison with the EDC model.

7.11.2 Boundary conditions

The oxidant and fuel inlets are defined as mass-flow-inlet boundary conditions based on the thermal power and an equivalence ratio of 0.9 (air-fuel ratio of 1.11) for all cases. The flue gas outlet is described as a pressure-outlet boundary condition. To prevent backflow, an option is enabled that converts cells with an adverse pressure drop into wall cells.

The heat loss through the furnace walls is modeled with the one-dimensional heat conduction equation using effective thermal conductivity for the wall material. The heat flux to the surroundings is given by radiation and convection. Wall emissivity is set to 0.62 and the natural convection heat transfer coefficient is estimated using the correlations of the Nusselt number for iso-thermal vertical and horizontal walls [21,22].

As mentioned before, the lab-scale furnace operates in batch mode as a transient heating/melting process with the thermal power controlled based on the operating temperature. For numerical analysis, the process load is modeled using a convective-like heat flow boundary condition at the horizontal plane representing the surface of the molten aluminum. The load heat flow boundary condition is defined using the aluminum melting temperature, 933 K (660 °C), and a heat transfer coefficient H . To keep the furnace at a controlled temperature while operating in a steady state, a thermal power of 100 kW is used as a reference with H equal to 240 W/m²/K. Higher thermal powers of 200 kW and 300 kW are evaluated, and the thermal load is

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increased by H equal to $720 \text{ W/m}^2/\text{K}$ and $1080 \text{ W/m}^2/\text{K}$, respectively, to maintain a roughly constant load temperature.

7.12 Results

7.12.1 Furnace performance

The results of the CFD simulations are used to evaluate the performance of the lab-scale furnace with the three burners. The next series of figures shows the contours of the temperature field at a vertical plane passing through the center of the burner for a thermal power of 100 kW. The shape of the reaction zone, corresponding to the high-temperature region, varies significantly with each burner. In the case of air combustion, a long flame extends towards the bottom of the furnace. The flame is longer with hydrogen combustion compared to methane (natural gas), due to the different burner head designed to inject the fuel and air with higher axial momentum. The

peak temperature for hydrogen combustion is over 200 K higher; however, it only results in an increase of around 20 K in the reference temperature at the ceiling. In the case of hydrogen-oxyfuel combustion with the LTOF burner, the reaction zone is more distributed, preventing a long flame and thus avoiding direct contact with the load. The temperature tends to be more homogeneous inside the furnace with the LTOF burner. However, a peak temperature over 3000 K occurs near the fuel injection point due to the oxygen flow of the pilot flame (1/10 of the total oxygen flow rate), which is maintained after ignition. The reference temperature at the ceiling increases around 100 K with hydrogen-oxyfuel combustion for the same thermal power of 100 kW.

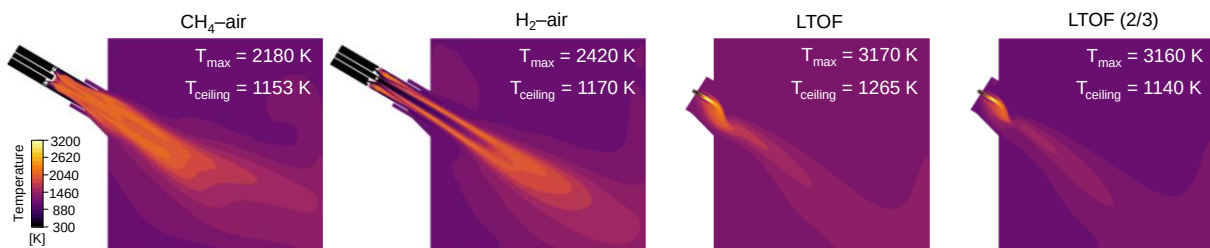


Figure 125: Temperature field contours at the burner vertical plane

The furnace heat balance from the CFD simulations is shown in the next figure. For the same thermal power, both air combustion burners present similar heat flows, with slightly higher energy transferred to the walls and load in the case of hydrogen as fuel. For hydrogen-oxyfuel combustion with the LTOF burner, the heat losses through the off-gas are significantly reduced due to the lower mass flow of flue gases. Consequently, more heat is transferred to the load. The thermal power needed with the LTOF burner is reduced by around one-third to achieve the same useful energy. Therefore, the evaluation of the burner's impact on furnace performance is done by comparing the hydrogen LTOF burner operating with two-thirds of the thermal power used for the cold air burners with methane and hydrogen (LTOF (2/3)). When the thermal power is adjusted for the LTOF burner, the heat transferred to the walls and load is similar to that of the cold air burner, while off-gas losses are further reduced.

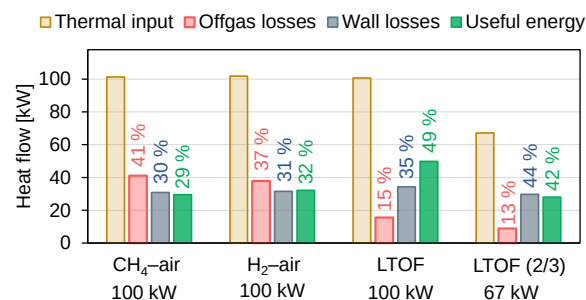


Figure 126: Furnace heat balance

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The thermal efficiency, defined as the ratio of useful energy (heat flow to the load) to the thermal input (thermal power), increases from 32% for hydrogen-air combustion to 42% for hydrogen-oxyfuel. The next figure presents the evolution of furnace performance with increasing thermal power. As mentioned above, the same useful energy is obtained with the LTOF burner operating with around two-thirds of the thermal power. Thermal efficiency increases with thermal power, reaching 63% for hydrogen-oxyfuel compared to 38% for hydrogen-air combustion. The increase in thermal efficiency with higher thermal power is primarily due to the increase in temperature inside the furnace, while the load temperature is kept constant by increasing the transfer coefficient as boundary conditions (similar to increasing the mass flow rate of the material to be heated).

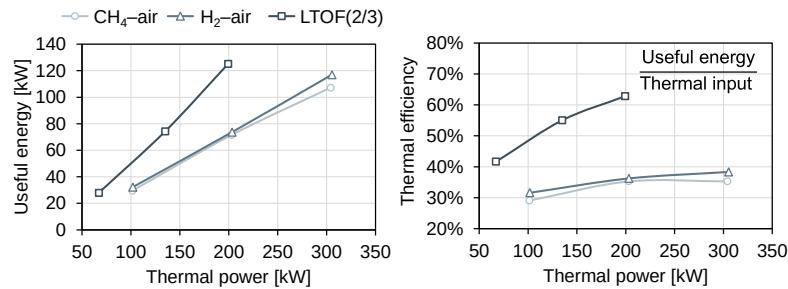


Figure 127: Useful energy and thermal efficiency for various thermal powers

The heat flux to the load is also presented in the next figure, showing that both radiation and convection heat fluxes increase with thermal power. Radiation represents around 90% of the heat flux to the load in the cases of air combustion, while it is around 80% in the case of oxyfuel combustion. This result is counterintuitive since radiation heat flux is usually reinforced by oxygen enrichment due to the higher partial pressure of radiative species in the flue gas (mainly CO₂ and H₂O), while convection is typically weakened due to the lower flue gas flow rate. Two effects may contribute to this result. Firstly, the volume of the lab-scale furnace is relatively low compared to an industrial furnace, with a mean optical beam length of around 0.8 m. Therefore, the impact of gas radiation is lower. Secondly, the high-speed oxygen injection in the LTOF burner may induce stronger convective currents inside the furnace, which increases convective heat transfer even with a lower mass flow rate.

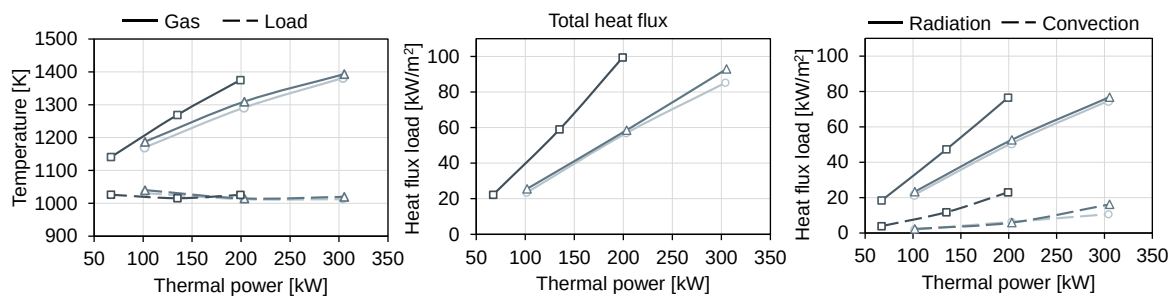


Figure 128: Mean temperature of the gas volume and the load surface and Heat flux to the load

To achieve high-speed injection, oxygen is introduced through small orifices using high-pressure lances. At high thermal power levels, sonic conditions are reached at the oxygen injection points, with shock diamonds observed in the simulation, as illustrated in the next figure. Preliminary tests of the LTOF burner revealed loud operational noise, likely associated with these high-speed flow conditions. To capture this effect in CFD simulations, a compressible density formulation must be considered for the flow.

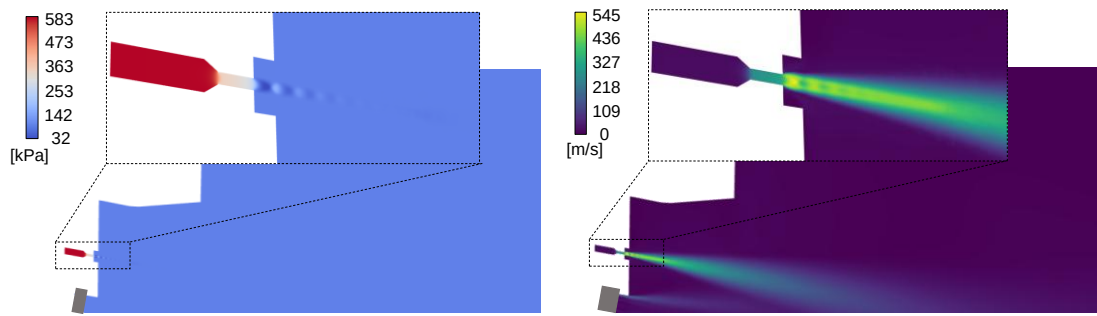


Figure 129: Absolute pressure and velocity magnitude for the oxygen injection in the LTOF burner at 200 kW

7.12.2 Combustion model evaluation

Although the combustion models for hydrogen combustion are addressed in more detail in Task 2.3, a preliminary evaluation is conducted to observe their impact on the results of furnace performance and the computational cost of the simulations. The EDC model with the DRM19 mechanism is compared with the EDC model with global mechanisms and the FGM model. The operating condition with a thermal power of 100 kW is used as a reference for the three burners.

The contours of the temperature field at a vertical plane passing through the center of the burner are presented in the next series of figures. Variations in the exact shape and temperature of the reaction zone are observed in all cases. For methane-air combustion, both the EDC-GM and FGM models predict higher temperatures near the burner tube wall, resulting in a different flow field with a narrower flame downstream. In the case of hydrogen-air combustion, the difference in the flow field at the reaction zone is smaller because the burner is modified to have lower fuel-air premixing before the reaction occurs. This simplifies the prediction of the flame location since the reaction is mainly controlled by the mixing process making it less sensitive to the finite-rate chemistry. However, visible differences in temperature are presented downstream of the burner.

In the case of the LTOF burner, notably higher discrepancies are observed, particularly around the flame produced by the pilot oxygen flow. Similar to air combustion, the peak temperature is overpredicted by the GM model. However, this deviation is more pronounced in oxyfuel combustion, as expected based on the adiabatic flame temperatures depicted in the next series of figures. In contrast, the FGM model predicts lower temperatures and a more compact reaction zone for the LTOF burner. It is known that the MILD combustion regime is challenging to model with the FGM since the flamelet regime differs from a distributed reaction zone [23,24]. The unity-Lewis assumption of the standard FGM model may also play a role in the results of reaction zone prediction.

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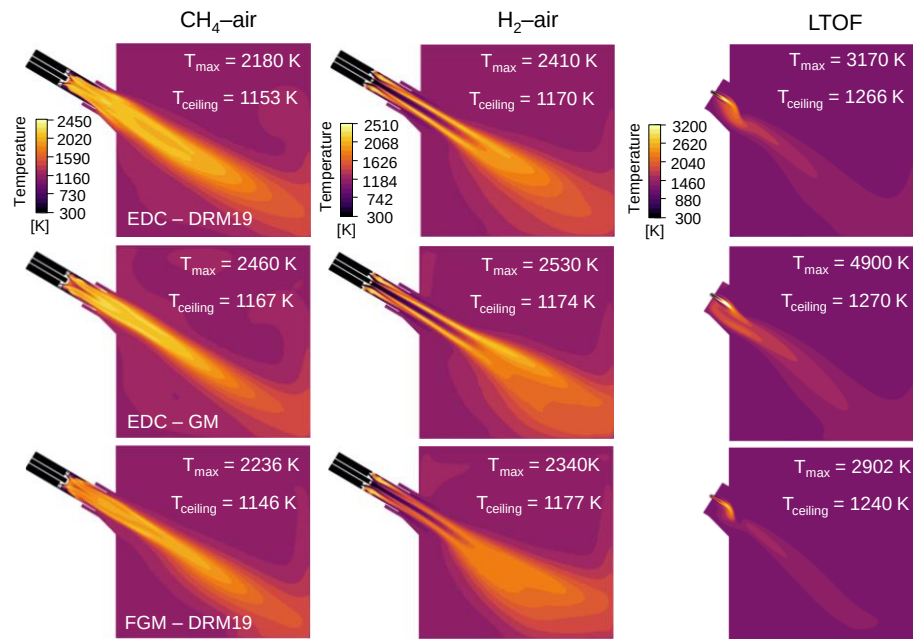


Figure 130: Effect of combustion model on the temperature field

Despite the differences in the reaction zone, the heat flows in the furnaces are slightly affected by the combustion model, as shown in the next figure. The errors in the heat flows are less than 3% for air combustion cases and less than 5% for oxyfuel combustion cases. The minor effect of the combustion model on the heat balance is due to the fact that the temperature and composition (concentration of major species) of the flue gas do not differ significantly between the models used. Consequently, the heat transfer by radiation and convection from the flue gas to the walls and load is not significantly affected.

On the other hand, the computational cost is drastically reduced when switching to a global mechanism with the EDC model, and even more so when the FGM model is used, as only four control variables are transported in the CFD instead of the species in the mechanism. Compared with the reference model (EDC – DRM19), the wall-clock time is approximately 56% lower when the GM is used and around 70% lower when the FGM model is used.

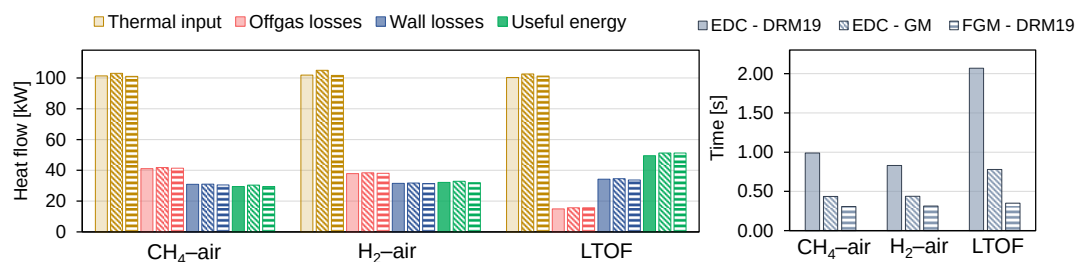


Figure 131: Effect of combustion model on furnace heat balance and wall-clock time per iteration per 100k cells using 30 cores

Since the focus of the current analysis was to evaluate the effect of the burner and the fuel-oxidant mixture on the furnace energy performance, the results are not too sensitive to the combustion model. Nevertheless, the relevance of the combustion model is expected to be high in other cases. For example, when the analysis focuses on burner design, where the correct prediction of the position and temperature of the reaction zone is needed to avoid flame flashback and/or blow-off and to ensure that the materials of the burner are not exposed to excessive temperatures.

7.12.3 Burner position

The simulations of the LTOF burner revealed that its location in the melting furnace causes flame deflection due to a negative pressure area near the burner below the jets for the lower thermal powers. This issue was confirmed during the preliminary installation of the burner, as shown in the next figure. The flame deflection leads to direct impact on the furnace wall, posing a risk of refractory damage. To resolve this, the burner position was adjusted in additional simulations, evaluating placements 50 mm, 100 mm, and 200 mm forward of the original location. The results indicate that moving the burner 100 mm forward was sufficient to eliminate flame deflection and wall contact, maintaining furnace performance while protecting the refractory material. The test of the burner after the final installation confirms the correct flame shape and no wall contact.

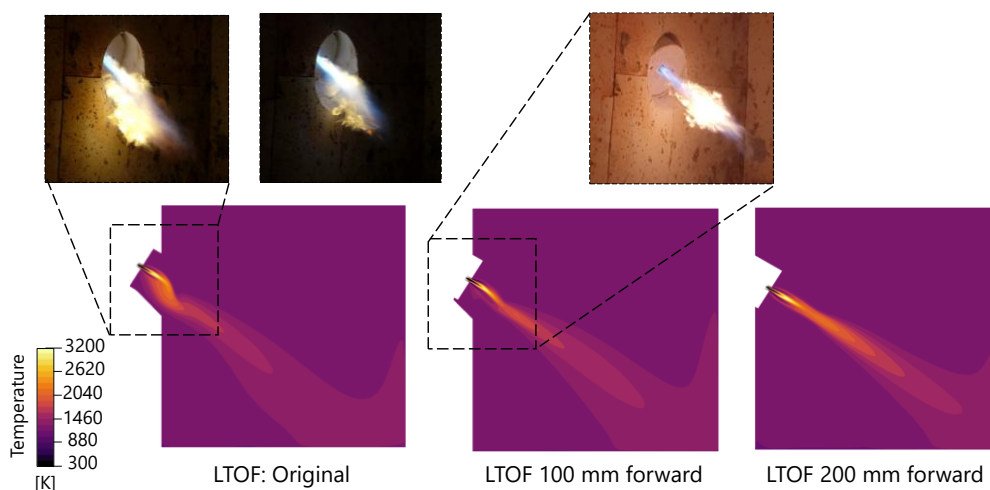


Figure 132: Evaluation of the position of the LTOF burner

7.12.4 NO_x emissions under air leakage conditions

In an oxyfuel system, combustion occurs with oxygen rather than air. Because nitrogen is removed from the reactant streams, ideal operation results in no NO_x formation during combustion. In practice, however, it is difficult to eliminate nitrogen entirely, and even small residual amounts of N₂ can lead to significant NO production, driven by the high flame temperatures characteristic of oxyfuel combustion [25]. Nitrogen may inadvertently enter the combustion system from several sources. It can be chemically bound within the fuel, such as in ammonia, or present in small quantities, as is the case with natural gas. In addition, the oxygen used in oxyfuel combustion is seldom completely pure; oxygen from air separation units typically has a purity of about 90–99% and therefore contains some nitrogen [26,27]. Despite being designed as airtight, oxyfuel furnaces can experience slight negative pressures or sealing imperfections that allow ambient air to be drawn in through wall penetrations, burner ports, flanges, or door openings.

The LTOF burner is designed to operate in flameless combustion with a gradual and limited temperature rise, potentially minimizing thermal NO_x formation even when trace amounts of nitrogen are present in the furnace. Simulations of a semi-industrial aluminum melting furnace equipped with the LTOF burner are carried out at a thermal power of 100 kW to evaluate NO_x formation in hydrogen-oxyfuel combustion under conditions of air leakage. Three combustion modes are compared depending on whether oxygen is injected through the central nozzle or the lateral lances, as illustrated in the next figure: Flame mode, when oxygen is injected through the central nozzle; Flameless mode, when oxygen is injected through the lateral lances; and Semi-flameless mode, when 15% of the oxygen is injected through the central nozzle and the remaining oxygen through the lateral lances.

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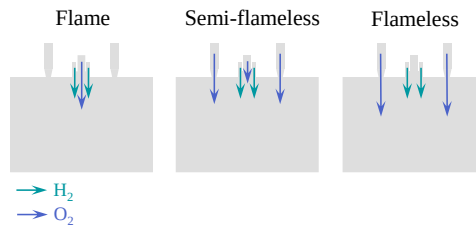


Figure 133: Diagram of the LTOF burner injection scheme

The thermal input is maintained at 100 kW with a global equivalence ratio of 0.9, corresponding to hydrogen and oxygen flow rates of 109.9 and 59.4 Nm³/h, respectively. Air leakage is modeled as a surface flux source of O₂ and N₂ over a 0.093 m² area located at the bottom of the furnace door as shown in the next figure. The leakage flow corresponds to 10% of the combined hydrogen–oxygen volumetric inflow to the furnace (16.6 Nm³/h), resulting in an increase of approximately 2% in the oxygen volume fraction of the exhaust gas. The temperature of the infiltrating air is assumed to be equal to the wall temperature, thereby avoiding the need to adjust the thermal input to maintain an operating temperature of approximately 1220 K at the furnace ceiling.

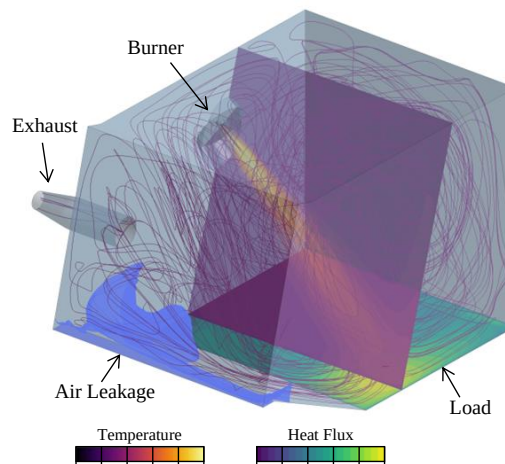


Figure 134: Computational domain of the lab-scaled furnace with the LTOF burner and air leakage

Although it has a higher computational cost, the EDC model is used for these simulations due to the higher accuracy to predict pollutant emissions and low-speed chemistry as the case of NO_x emissions and Flameless combustion.

Hydrogen oxidation is modeled using the H₂–O₂ chemistry subset of the C3MechLite kinetic mechanism [28], together with the associated NO_x reaction scheme. This mechanism has the best performance for hydrogen–oxyfuel according with the evaluation performed in the Task 1.4. The next figure (a) presents laminar flame speed predictions obtained from one-dimensional freely propagating flame simulations compared with experimental data and with predictions from other kinetic mechanisms, including CRECK [29,30], the UC San Diego [30], and the GRI 3.0 [31]. Substantial discrepancies are observed between the mechanisms, with C3Mech and UCSD exhibiting closer agreement with the available experimental data. It should be noted that experimental measurements of laminar flame speeds for hydrogen oxyfuel combustion are relatively scarce. When H₂O dilution is included, as in hydrogen–oxygen flue gas recirculation scenarios, the differences among the mechanisms are reduced, as illustrated in the next figure (b).

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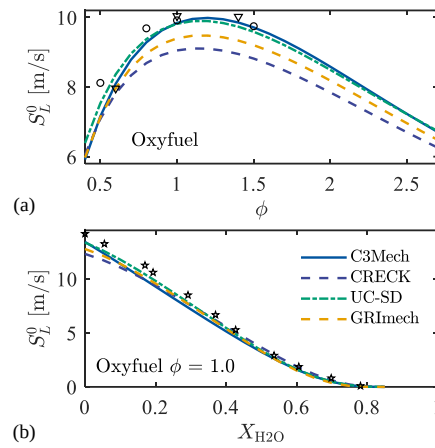


Figure 135: (a) Hydrogen-oxyfuel unstretched laminar flame speed as a function of the equivalence ratio ϕ , $T_u = 300$ K, and for (b) stoichiometric hydrogen-oxyfuel combustion with H_2O dilution, $T_u = 390$ K. Markers correspond to experimental data [32–38]

Because experimental data on NO emissions from canonical hydrogen–oxyfuel flames are not available in the literature, NO predictions from the different kinetic mechanisms are evaluated using a one-dimensional counterflow non-premixed flame under reference conditions representative of the lab-scale furnace simulations. The analysis accounts for air leakage as well as H_2O dilution in both the hydrogen and oxygen streams, with three dilution levels considered. The next figure shows the resulting temperature and NO mole fraction profiles across the counterflow flame. All mechanisms yield comparable NO production across the range of dilution cases. This limited sensitivity to the choice of mechanism is attributed to the predominance of the thermal NO pathway at the elevated flame temperatures and radical concentration typical of oxyfuel combustion. Since the thermal NO (Zel'dovich) mechanism is well established, its treatment is relatively consistent across kinetic mechanisms.

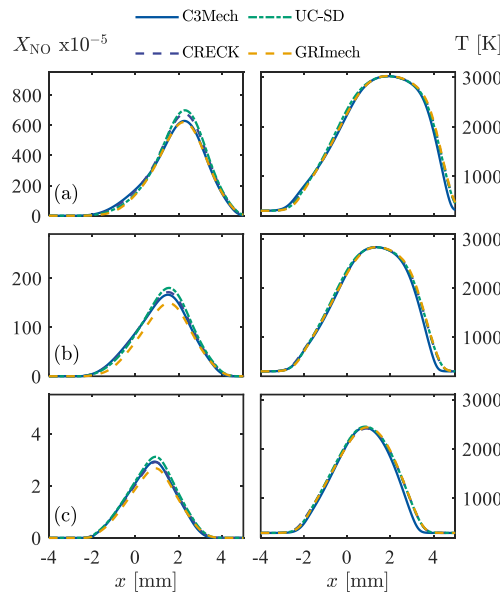


Figure 136: Profiles of temperature and NO mole fraction in a non-premixed counterflow hydrogen oxyfuel flame with 10% leaking air and H_2O dilution of (a) $X_{H_2O} = 0.0$, (b) $X_{H_2O} = 0.2$, and (c) $X_{H_2O} = 0.4$. $T_u = 300$ K and $\phi = 0.9$. Inlet separation equal to 12.7 mm and mean strain rate equal to 75 s^{-1} .

The LTOF show comparable energy performance operating under all three combustion modes. However, the spatial distribution of the reaction zone differs markedly, as illustrated in the next series of figures, which presents temperature and OH mass fraction contours at the burner. In flame mode, where oxygen is supplied

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through the central nozzle, a well-defined flame brush is evident in both the temperature and OH fields. In contrast, under semi-flameless operation, with only 15% of the oxygen injected through the central nozzle, the flame region becomes much smaller and combustion proceeds further downstream in a more distributed manner. In the flameless mode, where all oxygen is delivered through high-velocity lances, no distinct flame structure is observed; instead, combustion takes place within a broadly distributed reaction zone characterized by a small temperature rise and low concentrations of radicals such as OH.

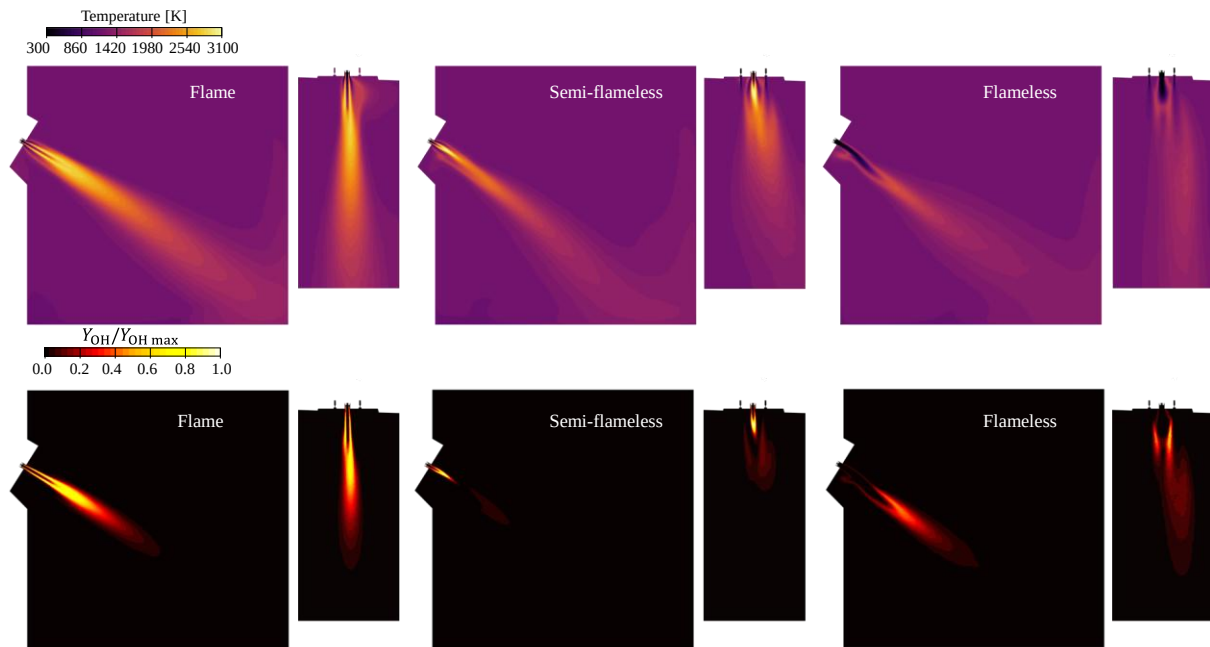


Figure 137: Contour plots of temperature and normalized OH mass fraction in the vertical and horizontal planes relative to the burner axis

The peak temperatures are 3007 K, 3068 K, and 2017 K for flame, semi-flameless, and flameless modes, respectively, while the off-gas temperature remains nearly constant at about 1192 K for all cases. Although the preheating temperature of the reactants resulting from internal flow recirculation prior to ignition is difficult to quantify, it is clear that the temperature rise is substantially reduced in flameless operation, with an increase relative to the off-gas temperature that is approximately 1000 K lower than in flame mode.

The off-gas composition consists of 82.6% H₂O, 7.2% O₂, and 10.2% N₂ by volume, compared with the expected composition of 94.7% H₂O and 5.3% O₂ under zero air-leakage conditions. The combustion mode has a pronounced impact on NO emissions. In flame mode, the NO volume fraction in the exhaust reaches 318.9 ppm, whereas in flameless mode it drops to 2.13 ppm, corresponding to a reduction of roughly three orders of magnitude. The semi-flameless configuration yields an intermediate NO level of 25.3 ppm, higher than in fully flameless operation but still substantially lower than in flame mode. The influence of combustion mode on temperature characteristics and NO formation is summarized in the next table. NO_x emissions (NO + NO₂) are additionally reported on a mass–energy basis, as recommended to prevent artificially high values for hydrogen–oxyfuel combustion relative to other fuels or air-fired systems [39].

Table 22: Comparison of temperature and NO_x emissions

Combustion mode	Flame	Semi-flameless	Flameless
Max. temperature [K]	3007	3068	2017
Mean temperature [K]	1231	1224	1220
Off-gas temperature [K]	1195	1191	1192

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$\Delta T = T_{\text{peak}} - T_{\text{offgas}}$	1812	1877	825
Off-gas NO [ppm v/v]	318.9	25.3	2.13
Off-gas NO ₂ [ppm v/v]	3.09	0.21	0.02
Off-gas NO _x [mg/kWh]	142.8	11.2	0.9

NO formation in all combustion modes is governed primarily by the thermal mechanism. Elevated NO production rates are observed in regions where the local mixture approaches stoichiometric conditions in the flame zone in both flame and semi-flameless modes, as temperatures and radical concentrations are highest there. As a result, intensified NO production in these high-temperature, radical-rich zone leads to increased NO levels, particularly in flame mode. On the other hand, in flameless mode or in the diluted zone of the semi-flameless mode, the distributed and diluted reaction zone results in lower peak temperatures and radical concentrations, and therefore in lower NO production rates.

Since leakage air constitutes the primary source of nitrogen responsible for NO formation, NO_x production is expected to depend strongly on the leakage air flow rate, or more specifically on the resulting nitrogen concentration within the furnace. To examine this effect across the three combustion modes, additional simulations are carried out for leakage air volumetric flow ratios of 5%, 15%, and 20%, corresponding to increases of 1.0%, 2.7%, and 3.4% in the off-gas O₂ wet volume fraction relative to the no-leakage case.

The next figure presents the variation of NO_x emissions in the off-gas as a function of the leakage air flow ratio, together with the corresponding N₂ wet volume fraction. As anticipated, NO_x emissions increase with rising N₂ concentration for all combustion modes. An approximately linear relationship is observed between NO_x emissions (mg/kWh) and the N₂ concentration (v/v, wet) in the exhaust. The slope of this linear trend reflects the sensitivity of NO_x formation to the presence of nitrogen and may vary depending on operating conditions, including furnace temperature, thermal input, and fuel composition [40].

In flame mode, NO_x formation shows a markedly greater sensitivity to N₂ concentration than in semi-flameless and flameless regimes. The slope of the linear correlation is approximately 14.1 mg/kWh per %N₂ in flame mode, whereas it drops to about 0.08 mg/kWh per %N₂ under fully flameless conditions. For semi-flameless operation, which represents a compromise between combustion stability and reduced NO_x emissions, the sensitivity increases moderately to around 1.12 mg/kWh per %N₂. This relatively limited sensitivity enables effective emission control even in the presence of unavoidable air ingress, for example during furnace door opening for material charging and discharging, when fully flameless conditions cannot be sustained.

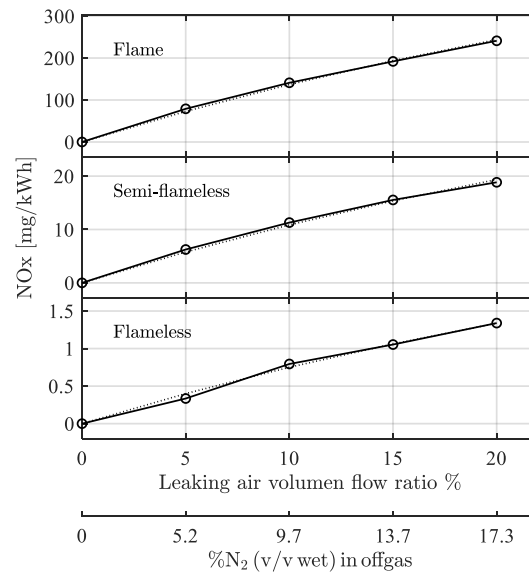


Figure 138: Effect of leaking air flow ratio on NOx emissions

7.13 Conclusions

- The melting trials with the Low Temperature Oxyfuel (LTOF) burner are an important complement to the experiments conducted in 2023 with a cold-air burner. They confirm expectations that using an oxyfuel burner allows for significantly improved fuel utilization, and that, with appropriate technology—in the case of the LTOF burner, oxygen lances—the problem of increased NOx formation caused by higher combustion temperatures can be reliably controlled.
- However, the trials have also shown that special care is required in adapting the furnace when switching to this different type of burner. Although the total gas flow circulating in the furnace is reduced with oxyfuel burners, the high velocity of the oxygen lances generates significant shear stresses at the melt surface when the burner orientation remains unchanged. These stresses can tear the protective oxide layer and, in combination with the available oxygen, lead to increased oxidation of the melt. It is therefore necessary to modify the positioning and alignment of the burner compared with the conventional installation used for cold-air burners.
- Furthermore, the trials underline the need to carefully control furnace pressure and to minimize furnace leakages, as the high velocities of the oxygen lances can locally create negative pressure, which may draw in false air and thus contribute to an increase in NOx levels.
- Compared to the challenges involved in converting the burner system from cold air to oxyfuel operation, the observed differences between the natural gas fuel and hydrogen are rather negligible regarding energy efficiency, melting rate, dross formation and hydrogen absorption by the melt.
- Considering the limitations mentioned, it can be concluded that, given a sufficient supply of green hydrogen, a conversion of existing melting facilities to low-CO₂ production is feasible without significant impact on melt quality.
- Using hydrogen-oxyfuel combustion increases thermal efficiency by approximately 10 percentage points with allows reducing the thermal power consumption by about one-third for the same heating load. The low-temperature oxyfuel (LTOF) burner design by Linde ensures a distributed reaction zone, preventing direct flame impact on the load and promoting homogeneous temperature distribution. However, the oxygen flow of the pilot flame, which remains after the ignition phase, results in a peak temperature exceeding 3000 K near the fuel injection point.

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- Regarding the combustion model (chemical scheme or turbulence-chemistry interaction), although it visibly affects the temperature and species distribution in the flame zone, it has minimal impact on the furnace energy balance while significantly affecting the computational cost. However, when the focus of the simulation is prediction of pollutants such NO_x the species transported model like the EDC couple with a detail or reduced mechanism is still required.
- The RANS simulations with detailed chemistry used to assess the influence of air leakage on NO emissions for hydrogen-oxyfuel combustion indicate that the transition from flame to flameless operation leads to a pronounced reduction in NO emissions. This reduction is mainly attributed to lower peak temperatures and more diluted reaction zones. Under flameless conditions, the NO volume fraction in the off-gas is reduced by approximately three orders of magnitude compared with flame mode. Semi-flameless combustion also achieves a significant decrease in NO emissions relative to flame operation. Across all regimes, thermal NO remains the predominant formation pathway, albeit with a reduced contribution under increasingly diluted conditions.
- Overall, these results demonstrate the effectiveness of the low-temperature oxyfuel burner in mitigating NO emissions while preserving stable operation with the semi-flameless mode in situations where fully flameless conditions are challenging to realize.

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8 Investigation of the Interactions of Refractory Materials with Hydrogen Combustion Atmospheres in the Aluminum Industry

8.1 Motivation and Introduction

One of the major challenges of the twenty-first century is ongoing climate change. This is particularly evident in the increase in global mean temperature and is driven to a considerable extent by the continuous release of climate-active greenhouse gases, including carbon dioxide (CO_2) and methane, as a result of human activities and industrialization. As the measures implemented to date have been insufficient to effectively mitigate climate change, a substantial reduction in global greenhouse gas emissions is required. Energy-intensive high-temperature processes, in particular, contribute significantly to global CO_2 emissions [1], [2]. Reducing these emissions therefore requires the increased substitution of fossil fuels with lower-emission alternatives. In this context, hydrogen is gaining increasing importance because its use does not produce carbon-containing combustion products and, when produced in a climate-neutral manner, it can serve as an energy carrier for low-emission industrial processes. The aluminum industry is a particularly energy-intensive sector. Accounting for approximately 8.2% of the Earth's crust, aluminum is the third most abundant element after oxygen and silicon and the most abundant metal. Owing to its low density, high specific strength, good corrosion resistance and excellent workability, aluminum is one of the most versatile engineering metals [3].

Global primary aluminum production amounted to approximately 74 million tons in 2025, with China accounting for the largest share at around 45 million tons. Melting and holding aluminum requires substantial amounts of thermal energy, which is currently supplied predominantly by natural gas combustion. Replacing natural gas with hydrogen represents a potential means of reducing CO_2 emissions from these processes. However, changing the fuel also alters the thermochemical conditions within the furnace. Whereas natural gas combustion produces carbon-dioxide-containing combustion products, the exhaust gas from hydrogen combustion consists predominantly of water vapor. Consequently, hydrogen-fired furnaces operate under atmospheric conditions characterized by a substantially higher water vapor content than those associated with conventional natural gas firing [4].

These altered atmospheric conditions impose additional chemical and thermal stresses on the refractory furnace lining. In aluminum melting furnaces, refractory materials are in direct contact with the molten metal. Owing to the high affinity of aluminum for oxygen, the melt can reduce oxide constituents of the refractory matrix. The resulting reactions may promote microstructural degradation, crack formation and penetration of the molten metal into the refractory material. To mitigate such infiltration, so-called non-wetting additives are incorporated into the refractory matrix. These additives reduce the wettability of the material by the aluminum melt by increasing the contact angle between the liquid metal and the solid surface. Additives used for this purpose include calcium fluoride (CaF_2), aluminum phosphate (AlPO_4) and barium sulfate (BaSO_4) [5] [6].

The aim of this study is to systematically investigate the effects of hydrogen combustion atmospheres on the properties of refractory castables intended for use in aluminum melting furnaces. To this end, refractory castable specimens are exposed at two temperatures (950 °C and 1350 °C) for a holding period of 168 h under water vapor-containing and hydrogen-containing atmospheres. Subsequently, changes in mass, bulk density, open porosity are determined and the evolution of the material composition is analyzed.

8.2 Material identification and test setup

RWTH-GHI, in collaboration with Speira and C-Tec, investigated critical areas within various aluminium melting furnaces to identify suitable refractory materials for prioritised testing. The investigation identified two particularly critical areas in which the refractory lining is exposed to severe operating conditions: the regions surrounding the burners and the bellyband area of the furnaces.

In the combustion zones, the gas flow can result in increased mechanical and thermal stresses. In addition, direct flame impingement on the refractory lining may occur, potentially leading to the formation of localised hot spots. Furthermore, under fuel rich (sub stoichiometric) hydrogen combustion conditions, the reducing atmosphere may promote the reduction of oxide constituents in the refractory material.

In total, two different materials with two different anti-wetting agents were identified, the possible changes of which in a water vapor-containing atmosphere are to be investigated.

Material 1: High alumina castable based on Al_2O_3 - SiO_2 (Medium cement castable)

Anti-wetting agent: Barium sulfate (BaSO_4)

Table 23: Chemical composition of Material 1 according to the manufacturer's specifications

Chemical composition	Al_2O_3	SiO_2	BaO	CaO	Fe_2O_3
Portion [wt.-%]	61,0	26,0	6,7	3,0	0,9

Material 2: High alumina castable based on Al_2O_3 (chemically bound with phosphoric acid)

Anti-wetting agent: Aluminum phosphate (AlPO_4)

Table 24 Chemical composition of Material 2 according to the manufacturer's specifications:

Chemical composition	Al_2O_3	P_2O_5	MgO	SiO_2	Fe_2O_3
Portion [wt.-%]	85,0	5,4	2,9	2,4	0,8

To carry out the planned tests, samples with dimensions of 150 mm x 25 mm x 25 mm will be produced (Figure 139).

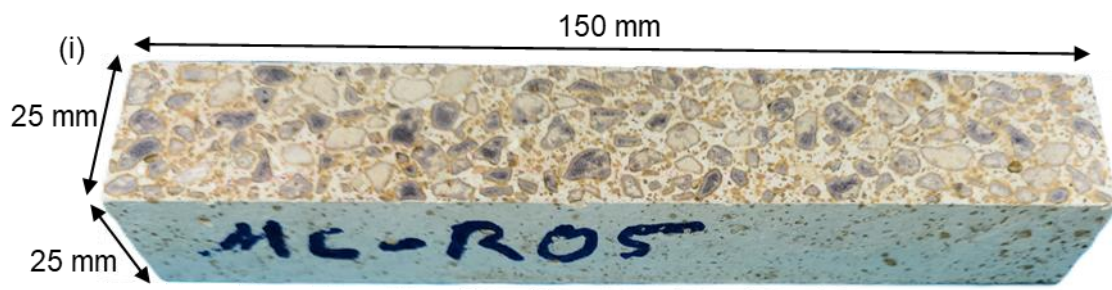


Figure 139: Illustration of the samples with characteristic dimensions

A tube furnace from the company Therma-Aix is used for the test. The furnace atmosphere can be defined and adjusted via a mixing system from Bronkhorst. The furnace consists of an oven housing and an oven tube, which is heated via electric heating elements. The furnace tube made of high-purity α - Al_2O_3 corundum with

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a purity of more than 99.5% has an inner diameter of 55 mm and a length of 1200 mm. Both pipe ends are closed with oil-tempered metal flanges, each with five connections. Four connections are used to cool the seals via a water pipe. Another connection is provided for gas inlet and outlet.

As already described, the gas inflow for the furnace atmosphere is generated via a mixing system. The mixing system is connected to pressurized gas cylinders mounted at the rear of the test stand. This allows hydrogen or argon to be introduced into the tube furnace. Additionally, the system can generate water vapor and introduce it into the gas stream. This involves using tap water, which is first cleaned via a filter system. Water is dispensed before evaporation via the Mass flow. The gases are volumetrically controlled and serve as a carrier medium for the water vapor. The resulting gas-water vapor mixture is introduced into the furnace via a supply line heated to 150 °C to prevent condensation of the water. The flanges are tempered to 130 °C for the same reason. The exhaust gas from the furnace is directed into a water bath, thus preventing both a backflow of the exhaust gas and the ingress of ambient air. In this way, the experimental conditions remain stable. Furthermore, the water bath allows the condensation contained in the exhaust gas to be absorbed. The schematic structure can be seen in Figure 140.

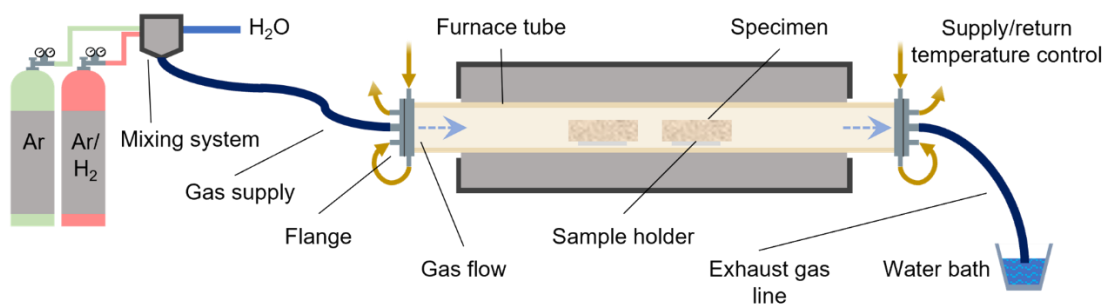


Figure 140: Schematic illustration of the experimental setup

Four trials are conducted for each material. These are referred to as main experiments (MT) and differ in temperature (950 °C and 1350 °C) as well as the atmospheres used (Ar+H₂O and Ar/H₂ as carrier gas +H₂O). The hydrogen is fed into the system as a gas consisting of 10% hydrogen and 90% argon. The duration of each test is 168 hours. For Material 1, three samples were tested per trial in the tube furnace. For Material 2, the test setup was slightly modified, and the number of samples per trial was reduced to two.

The low temperature of 950 °C serves to compare the material behavior at moderate versus high temperatures and corresponds to the maximum operating temperature in an aluminum melting furnace. To investigate the stress and possible corrosion events near the temperature related application limit of the material, the higher test temperature is set at 1350 °C. The water vapor argon atmosphere reflects the atmosphere of complete hydrogen combustion. The use of forming gas as a carrier gas (Ar/H₂+H₂O) reflects the case of incomplete hydrogen combustion.

In addition to the main tests, reference samples (RT) are stored in a stone furnace at the same temperatures (950 °C and 1350 °C) and the same holding time in air. This serves to investigate the sole influence of temperature in order to assess whether observed changes in the material are solely due to temperature or also to the atmosphere.

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Table 25: Overview of the experiments conducted on Material 1

Experiment	Sample (Pos.1)	Sample (Pos.2)	Sample (Pos.3)	Temperature [°C]	Atmosphere
MT-1-0		R1-0		Sample after sintering	
MT-1-1	R1-1	R1-2	R1-3	950	Ar+H ₂ O
MT-1-2	R1-4	R1-5	R1-6	1350	Ar+H ₂ O
MT-1-3	R1-7	R1-8	R1-9	950	Ar/H ₂ +H ₂ O
MT-1-4	R1-10	R1-11	R1-12	1350	Ar/H ₂ +H ₂ O

Table 26: Overview of the experiments conducted on Material 1

Experiment	Sample (Pos.1)	Sample (Pos.2)	Temperature [°C]	Atmosphere
MT-2-0		R2-0	Sample after sintering	
MT-2-1	R2-1	R2-2	950	Ar+H ₂ O
MT-2-2	R2-3	R2-4	1350	Ar+H ₂ O
MT-2-3	R2-5	R2-6	950	Ar/H ₂ +H ₂ O
MT-2-4	R2-7	R2-8	1350	Ar/H ₂ +H ₂ O

Measurements of mass, bulk density and open porosity are carried out for all test bars used. Additionally, the elastic modulus of these samples at room temperature is determined using resonance frequency damping analysis (RT-RFDA). All analyses listed so far are first carried out with complete test bars in the state after sintering and repeated with the same test specimens after the trials in order to quantify any changes resulting from the thermo-atmospheric action.

Further analytical methods, which are carried out to characterize chemical composition. Due to the destructive nature of sampling, a before-and-after comparison of the same samples is not possible. The sample after sintering serves as a reference to the samples after the trials. The following investigations were carried out on this and on selected outsourced samples: X-ray diffraction analysis (RBA) for phase identification, X-ray fluorescence analysis (RFA) to determine the chemical composition. The sampling points of the respective samples along the gas flow direction of the deposition tests, as well as the approximate dimensioning of the extracted sections, are shown schematically in Figure 141. The powdered sample material with a grain size $\leq 63 \mu\text{m}$ required for use in the RBA and the RFA is produced by completely grinding the intended bar sections with a disc vibratory mill.

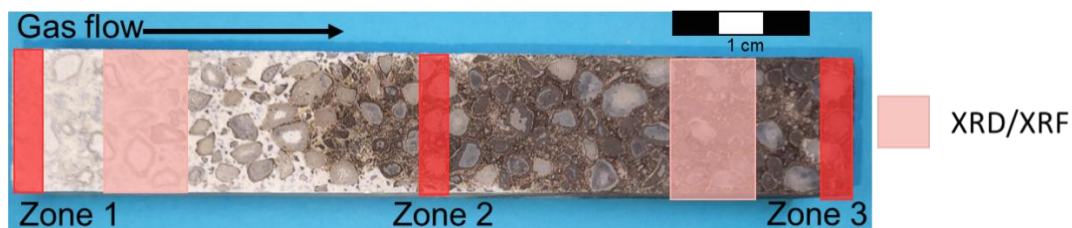


Figure 141: Sampling locations for the specimen sections used in subsequent analyses

8.3 Results

Material 1

Mass Changes

The mass changes are evaluated based on the percentage deviation from the initial weight in order to compare differences between test series and sample positions. They can provide initial indications of processes during outsourcing, such as mass transfers into the gas phase.

Figure 142 shows the relative mass changes of the bars depending on experimental conditions and furnace position. Overall, only slight changes in mass occur between +0.002% and –0.162%. In a water vapor atmosphere, the changes at 950 °C range between –0.014% and +0.001%. At 1350 °C, the mass losses of the front and middle bars increase to 0.069% and 0.076% respectively, while the rear bar remains almost unchanged (+0.002%).

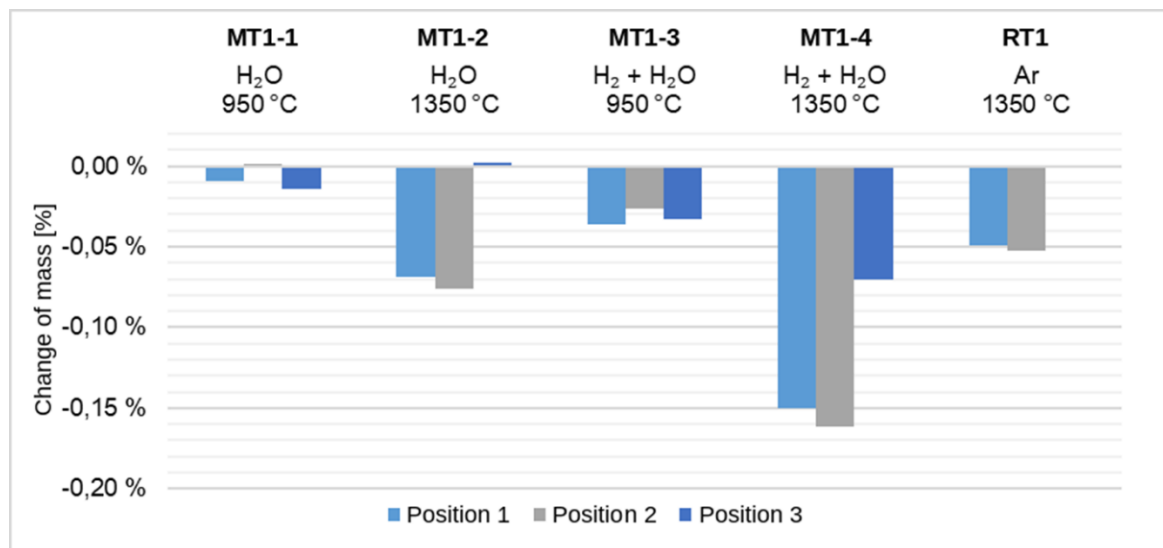


Figure 142: Mass changes of Material 1 resulting from the exposure tests

Mass losses are higher in hydrogen-containing atmospheres. At 950 °C, they range between 0.026% and 0.036%, and at 1350 °C, between 0.071% and 0.162%. The greatest loss occurs at position 2 (0.162%). Under argon at 1350 °C, mass losses are lower at 0.049% at position 1 and 0.052% at position 2.

Overall, mass losses tend to increase with rising temperature and are higher in hydrogen-containing atmospheres than in water vapor. Furthermore, position dependent differences are evident: At 950 °C, the outer bars lose more mass than the middle one. At 1350 °C, the middle bar shows the greatest losses, the front samples also show increased values.

Bulk density and open porosity

To assess changes caused by outlaying, bulk density and open porosity were determined before and after the tests. The characteristic values serve to assess changes in density and pore space. The average bulk density in the initial state is $2.45 \pm 0.02 \text{ g/cm}^3$. After the trials, the relative changes in bulk density remain predominantly small. At 950 °C, they range between –0.12% and +0.09% in both atmospheres. The bulk density decreases exclusively at the front bars, while the middle and rear bars show an increase. At 1350 °C, stronger changes occur, especially under hydrogen-containing atmospheres at the front (+1.21%) and rear bars (+1.10%) and under argon at the middle bar (+1.10%). Furthermore, a position dependent tendency is evident: the outer bars become denser, while the middle ones exhibit a decrease in bulk density.

The open porosity in the initial state averages $21.68 \pm 0.40 \text{ vol\%}$. The relative changes after trials are predominantly small (Figure 143). Under water vapor, they range between 1.31% and +0.33% at 950 °C and

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between 0.21% and +1.31% at 1350 °C. The middle bars each show the strongest deviations, while the outer ones remain largely unchanged.

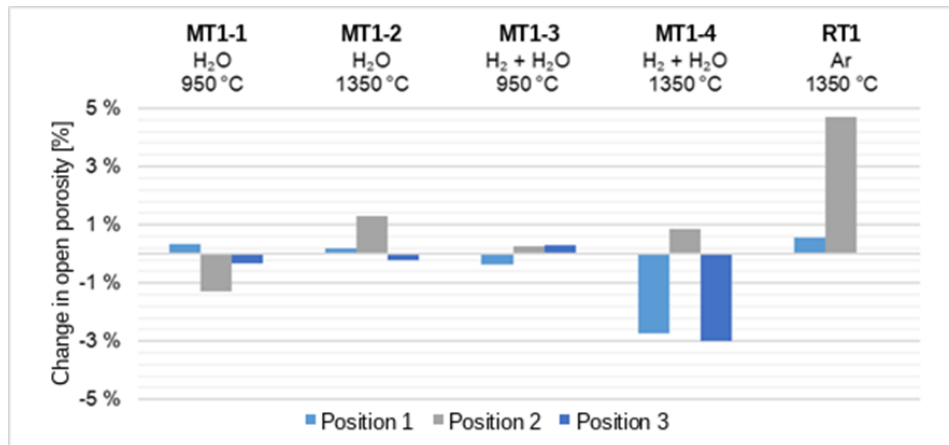


Figure 143: Changes in the Porosity of material 1 resulting from the exposure tests

In a hydrogen-containing atmosphere, the porosity hardly changes at 950 °C (–0.36% to +0.29%). At 1350 °C, however, the greatest reductions in porosity occur: 2.75% at the front bar and 2.99% at the rear bar. In contrast, the middle bar shows a slight increase of 0.87%. Under argon at 1350 °C, the strongest porosity increase of the entire series of experiments (+4.71%) is observed in the middle sample. The porosity of the middle sample also increases in the other experiments at this temperature. Overall, however, no clear dependence of the porosity changes on the sample position can be identified.

Influence on E-modulus (RT-RFDA)

To investigate potential structural changes, the modulus of elasticity is determined before and after trials using RFDA at room temperature. The absolute measured values, including tolerances and relative changes, are shown in Table 27. For most experimental conditions, the modulus of elasticity decreases; stiffness increases occur exclusively at 1350 °C.

Table 27: Changes in the Young's modulus of Material 1 resulting from the exposure tests

Experiment	Position	E _{before} [GPa]	E _{after} [GPa]	ΔE [GPa]
MT1-1 (H ₂ O, 950 °C)	1	48,65 (± 1,30)	46,29 (± 1,24)	-2,36
	2	61,49 (± 3,56)	56,80 (± 3,28)	-4,69
	3	35,50 (± 0,71)	33,29 (± 0,66)	-2,21
MT1-2 (H ₂ O, 1350 °C)	1	44,43 (± 1,32)	40,47 (± 1,20)	-3,96
	2	55,30 (± 0,42)	56,92 (± 0,43)	1,62
	3	49,33 (± 2,34)	45,99 (± 2,18)	-3,34
MT1-3 (H ₂ , 950 °C)	1	38,16 (± 0,76)	36,46 (± 0,72)	-1,70
	2	53,81 (± 1,64)	50,93 (± 1,55)	-2,88
	3	51,87 (± 2,45)	49,74 (± 2,35)	-2,13
MT1-4 (H ₂ , 1350 °C)	1	35,17 (± 0,22)	40,95 (± 0,26)	5,78
	2	56,78 (± 1,02)	60,63 (± 1,09)	3,85
	3	41,44 (± 0,57)	47,08 (± 0,65)	5,64

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RT1 (Ar, 1350 °C)	1	48,15 ($\pm 2,01$)	48,92 ($\pm 2,04$)	0,77
	2	60,00 ($\pm 2,31$)	61,41 ($\pm 2,36$)	1,41

Figure 144 shows the relative modulus changes relative to the initial state of the respective bar. At 950 °C, decreases between -4.11% and -7.63% occur across positions both under water vapor and in hydrogen-containing atmospheres, with the middle bars showing the strongest changes.

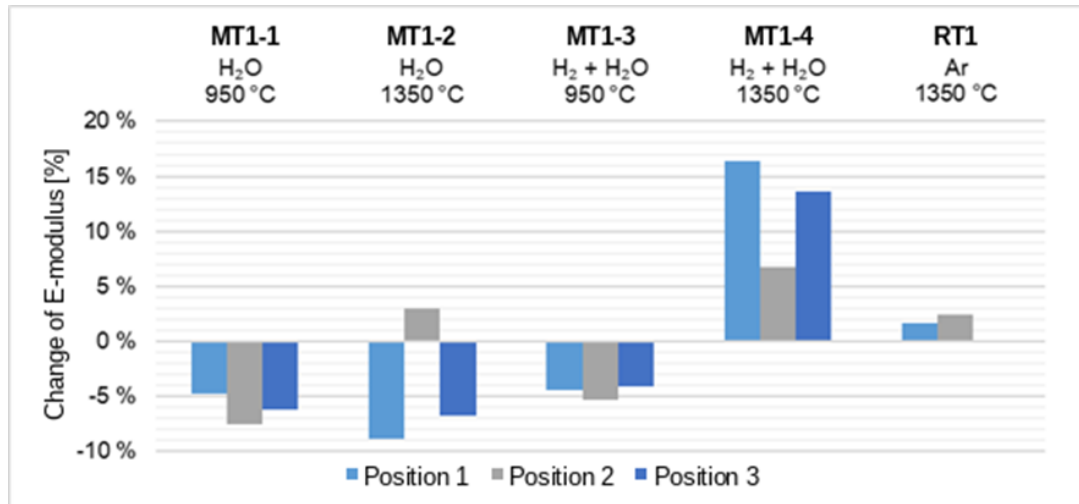


Figure 144: Relative change in Young's modulus due to exposure

At 1350 °C, a decrease is observed under steam at the front (-8.91%) and rear bars (-6.77%), while the middle bar shows an increase of 2.93% . In a hydrogen-containing atmosphere, the modulus of elasticity increases at all positions, especially at the front ($+16.43\%$) and rear bars ($+13.61\%$); at the middle bar, the increase is 6.78% . The control experiment under argon leads to small increases in stiffness of 1.60% at the front bar and 2.35% at the middle bar.

Chemical Composition (XRF)

To detect changes in chemical composition due to deposition, the samples are examined using X-ray fluorescence analysis (XRF). The measured values of the outsourced bar areas are compared with those of the sample after sintering.

The sample shown in Table 28 mainly contains Al_2O_3 (59.81 wt.%) and SiO_2 (26.53 wt.%). Other essential components are BaO (6.12 wt.%), CaO (3.23 wt.%), TiO_2 (2.05 wt.%) and Fe_2O_3 (1.13 wt.%). Components with individual contents ≤ 0.26 wt.% are combined.

Table 28: Chemical composition of Material 1 after sintering, determined by XRF

Chemical composition	Al_2O_3	SiO_2	BaO	CaO	TiO_2	Fe_2O_3	Rest
Portion [wt.-%]	59,81	26,53	6,12	3,23	2,05	1,13	1,13
Loss of ignition [wt.-%]	0,00						

The following comparisons focus on the six main components as well as the front and rear areas of the bar positioned at the front of the oven, respectively. Table 29 shows the results after outsourcing in a water vapor atmosphere at 950 °C (MT1-1) and 1350 °C (MT1-2).

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Table 29: Comparison of the chemical compositions determined by XRF before and after exposure tests in a water vapor atmosphere

Chemical composition	[wt.%]	Al ₂ O ₃	SiO ₂	BaO	CaO	TiO ₂	Fe ₂ O ₃	others	Total	Loss of ignition
MT1-0	After sintering	59,81	26,53	6,12	3,23	2,05	1,13	1,13	100	0
MT1-1 (H ₂ O, 950 °C)	Zone 1	59,94	25,75	6,55	3,65	1,94	1,08	1,09	100	0,05
	Zone 3	58,74	26,26	7,08	3,78	1,93	1,09	1,12	100	0,11
MT1-2 (H ₂ O, 1350 °C)	Zone 1	59,82	26,51	6,05	3,38	2,04	1,1	1,1	100	-0,03
	Zone 3	57,37	28,54	6,3	3,4	2,11	1,13	1,15	100	0,02

At 950 °C, the SiO₂ content in the front bar area drops to 25.75 wt.%, while CaO and BaO increase slightly. In the rear area, the Al₂O₃ content decreases from 59.81 to 58.74 wt.%, while BaO increases from 6.12 to 7.08 wt.%. Here too, the CaO content increases. According to measurements, the loss on ignition is 0.11% in the rear area and 0.5% in the front area.

At 1350 °C, the values in the front range remain largely unchanged. The negative loss on ignition of –0.03% indicates a slight increase in mass. In the rear area, the Al₂O₃ content decreases to 57.37 wt.%, while SiO₂ increases from 26.53 to 28.54 wt.%. The remaining components show only minor changes.

Table 30 then compares the RFA results after removal in a hydrogen-containing atmosphere at 950 °C (MT1-3) and 1350 °C (MT1-4) with the values of the zero sample.

Table 30: Comparison of the chemical compositions determined by XRF before and after exposure tests in a hydrogen-containing atmosphere

Chemical composition	[wt.%]	Al ₂ O ₃	SiO ₂	BaO	CaO	TiO ₂	Fe ₂ O ₃	others	Total	Loss of ignition
MT1-0	After sintering	59,81	26,53	6,12	3,23	2,05	1,13	1,13	100	0
MT1-3 (H ₂ , 950 °C)	Zone 1	60,61	25,39	6,43	3,46	1,99	1,09	1,03	100	0,03
	Zone 3	60,14	26,87	5,67	3,18	2,02	1,1	1,02	100	-0,04
MT1-4 (H ₂ , 1350 °C)	Zone 1	59,67	26,66	6,11	3,29	2,09	1,12	1,06	100	-0,03
	Zone 3	56,41	28,91	6,73	3,68	2,04	1,07	1,16	100	0,03

The results in Table 30 show temperature- and position dependent changes in chemical composition even after hydrogen-containing atmosphere. At 950 °C (MT1-3) the SiO₂ content in the front bar area decreases

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from 26.53 to 25.39 wt.%, while the Al_2O_3 content increases from 59.81 to 60.61 wt.%. CaO and BaO increase slightly. In the rear area, the changes are less pronounced; the oxide contents of aluminum and silicon are slightly above the initial values, while the BaO content drops to 5.67 wt.%. The loss of ignition is low in both areas.

At 1350 °C (MT1-4), the composition in the front area remains largely unchanged. In the rear area, the Al_2O_3 content decreases to 56.41 wt.%, while the SiO_2 content increases from 26.53 to 28.91 wt.%. BaO and CaO are also increasing slightly. The loss on ignition is weakly negative at the front and weakly positive at the rear.

Table 31: Comparison of the chemical compositions determined by XRF before and after exposure testing under argon

Chemical composition	[wt.%]	Al_2O_3	SiO_2	BaO	CaO	TiO_2	Fe_2O_3	others	Total	Loss of ignition
MT1-0	After sintering	59,81	26,53	6,12	3,23	2,05	1,13	1,13	100	0
RT1 (Ar, 1350 °C)	Zone 1	59,28	26,19	6,58	3,74	1,97	1,11	1,13	100	0,08
	Zone 3	56,89	28,36	6,77	3,77	2,01	1,09	1,11	100	0,02

Table 31 shows the results of the control experiment under argon at 1350 °C (RT1). In the front bar area, the levels of Al_2O_3 and SiO_2 decrease slightly, while BaO and CaO increase. In the rear area, the BaO and CaO components are also increased. The Al_2O_3 content decreases to 56.89 wt.%, while SiO_2 increases from 26.53 wt.% to 28.36 wt.%. The loss on ignition is 0.08% in the front area and 0.02% in the rear area.

Phase Analysis (XRD)

The phase compositions investigated using XRD before and after the trials are evaluated based on semi-quantitative comparisons of the diffractograms. The front and rear locking areas are considered separately according to the removal points shown in Figure 141.

In the initial state, six phases are identified: Mullite ($3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$), Corundum (Al_2O_3), Cristobalite (SiO_2), Celsian ($\text{BaAl}_2\text{Si}_2\text{O}_8$), Anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$) and Hibonite ($\text{CaAl}_{12}\text{O}_{19}$).

At 950 °C, all phases remain detectable regardless of the atmosphere and sample position. At 1350 °C, however, changes occur (Table 32 **Fehler! Verweisquelle konnte nicht gefunden werden.**). Cristobalite and hibonite are no longer detectable in the posterior bar regions. In the anterior regions, their peak intensities are slightly to moderately reduced.

The changes in the remaining phases depend on the experiment. In Celsian, after being deposited in steam, there is a slight increase in peak intensity at the front and a decrease at the rear. Under hydrogen and argon, the intensities remain largely unchanged. Mullite decreases in the posterior regions in all trials, slightly after MT1-2, moderately after MT1-4 and strongly after RT1. At the front, mullite remains unchanged after MT1-2, increases slightly after MT1-4 and decreases sharply after RT1.

The corundum intensity increases slightly at the beginning after MT1-2 and MT1-4, while no change is noticeable after RT1. Posteriorly, it increases slightly after MT1-2, sharply after MT1-4, and moderately after RT1. Anorthite shows increased peak intensities in all trials and in both bar areas. The increase is moderate at the front and slight at the rear after MT1-2. After MT1-4 and RT1 it is slight at the front and moderate at the rear.

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For comparative evaluation, the peak intensities of the samples deposited at 1350 °C were evaluated semi-quantitatively. Table 32 encodes the relative deviations compared to the zero sample: „=“ indicates unchanged intensities, „+“ to „+++“ slight to strong increases, and „–“ to „---“ corresponding decreases. „0“ denotes phase peaks that are no longer detectable.

Table 32: Semi-quantitative assessment of changes in the peak intensities of detected phases following exposure tests at 1350 °C relative to the sample after sintering

		Cristobalite SiO ₂	Celsian BaAl ₂ Si ₂ O ₈	Mullite 3 Al ₂ O ₃ ·2 SiO ₂	Corundum Al ₂ O ₃	Anorthite CaAl ₂ Si ₂ O ₈	Hibonite CaAl ₁₂ O ₁₉
MT1-2 (H ₂ O)	Zone 1	--	+	=	+	++	-
	Zone 3	0	-	-	+	+	0
MT1-4 (H ₂)	Zone 1	--	=	+	+	+	--
	Zone 3	0	=	--	+++	++	0
RT1 (Ar)	Zone 1	--	=	---	=	+	--
	Zone 3	0	=	---	++	++	0

Material 2

The column diagram in Figure 145 compares the mass changes of the bars depending on the experimental condition.

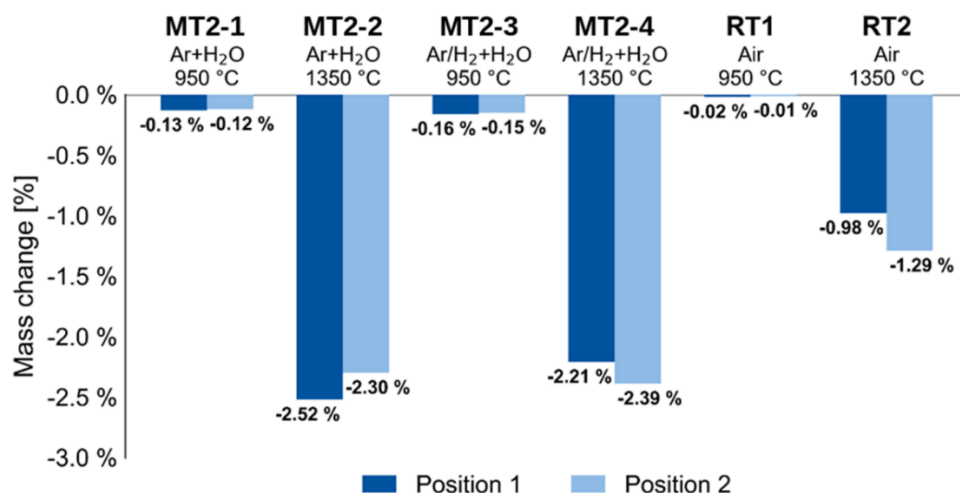


Figure 145: Mass changes of Material 2 resulting from the exposure tests

All samples show a mass loss after outsourcing, which is significantly lower at 950 °C than at 1350 °C.

At 950 °C, the reference samples (RT1, air) show low losses of –0.02% and –0.01%. Samples in a water vapor atmosphere (MT2-1) lose approximately 0.13%, those in a hydrogen-containing atmosphere (MT2-3)

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approximately 0.16%. The sample position has no discernible influence. The absolute mass losses are approximately 0.30 g (MT2-1) and 0.42 g (MT2-3) per sample, respectively.

At 1350 °C, mass losses increase significantly. The reference samples (RT2, air) show losses of –1.29% and –0.98%. In a water vapor atmosphere (MT2-2), the highest losses are measured at –2.52% and –2.30%, corresponding to 6.7 g and 6.3 g per sample, respectively. Samples in hydrogen-containing atmospheres (MT2-4) show comparable losses of –2.21% and –2.39% (5.5–6.3 g per sample).

Bulk density and open porosity

To assess structural changes, bulk density and open porosity are determined before and after outsourcing. The relative changes are shown in Figure 146. Depending on the experimental conditions, both sample positions in the tube furnace are compared.

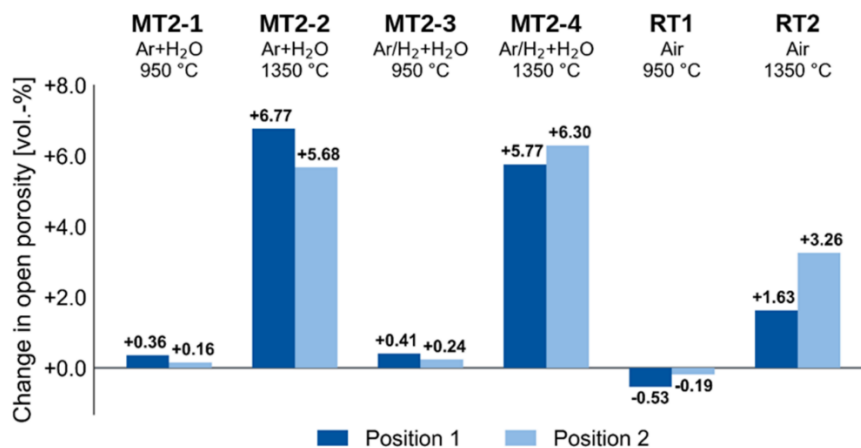


Figure 146: Changes in the Porosity of material 2 resulting from the exposure tests

At 950 °C, the bulk density remains almost constant and deviates from the initial value by a maximum of 0.02 g/cm³. At 1350 °C, it decreases by up to 0.11 g/cm³ in the water vapor-containing atmospheres (MT2-2, MT2-4). The air reference (RT2) shows lower decreases of 0.02–0.04 g/cm³.

The open porosity also changes only slightly at 950 °C. It increases by 0.16–0.36% at MT1-1 and by 0.24–0.41% at MT2-3, while the air reference (RT1) shows a decrease of up to 0.5%.

At 1350 °C, the increase in porosity is significantly greater: In a water vapor atmosphere (MT2-2) it is up to 6.8%, in a hydrogen-containing atmosphere (MT2-4) up to 6.3%. The air reference (RT2) shows a smaller increase of up to 3.3%.

Influence on E-modulus (RT-RFDA)

To detect structural changes, the Young's modulus is determined before and after outsourcing at room temperature. Both sample positions are considered separately. Table 33 contains the measured values including standard deviations as well as the differences between the initial and final states.

The changes in the modulus of elasticity are mostly small and usually lie within the respective standard deviations (± 2.4 to ± 13.8 GPa). No systematic influence of the atmosphere or deposition temperature is apparent in the main experiments. MT2-4 at position 2 is an exception, with an increase of 6.4 GPa. In the reference experiments, the modulus of elasticity increases predominantly by up to 8.7 GPa. Only RT1 (R13) shows a slight decrease of 2.24 GPa.

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Table 33

Experiment	Position	E _{before} [GPa]	E _{after} [GPa]	ΔE [GPa]
MT2-1	1	116,84 (± 2,71)	120,49 (± 2,8)	+3,65
MT2-1	2	118,32 (± 6,66)	116,31 (± 8,54)	-2,01
MT2-2	1	137,68 (± 4,43)	134,4 (± 4,33)	-3,28
MT2-2	2	133,27 (± 6,3)	133,59 (± 6,32)	-0,32
MT2-3	1	111,67 (± 2,41)	109,45 (± 2,36)	-2,22
MT2-3	2	129,42 (± 10,62)	130,84 (± 10,73)	+1,42
MT2-4	1	141,33 (± 4,03)	141,21 (± 4,03)	-0,12
MT2-4	2	124,17 (± 6,08)	130,57 (± 6,4)	+6,4
RT1 (R13)		139,58 (± 2,7)	137,34 (± 2,65)	-2,24
RT1 (R14)		134,3 (± 4,15)	143,02 (± 4,42)	+8,72
RT2 (R15)		114,45 (± 12,99)	121,64 (± 13,81)	+7,19
RR2 (R16)		132,11 (± 2,36)	140,78 (± 2,54)	+8,67

Chemical composition (XRF)

The sample after sintering as well as MT2-1 (950 °C, Ar+H₂O), MT2-2 (1350 °C, Ar+H₂O), MT2-4 (1350 °C, Ar/H₂+H₂O) and RT2 (1350 °C, air) were analyzed using XRF. All measurements were taken in Zone 1. Table 34 shows the six main oxides. Components with contents ≤ 0.3 wt.% are grouped under „Others“.

Table 34: Chemical composition (XRF) of the reference sample and the exposed samples (material 2)

Oxide [wt.-%]	Al ₂ O ₃	P ₂ O ₅	SiO ₂	TiO ₂	MgO	Fe ₂ O ₃	Others	Loss of ignition
After sintering	86,14	4,37	2,59	2,29	2,57	1,01	0,84	0,18
MT2-1	85,55	4,36	2,92	2,33	2,51	1,07	9,86	0,14
MT2-2	87,55	3,84	2,29	2,15	2,47	0,96	0,72	0,01
MT2-4	87,26	3,45	2,45	2,26	2,61	0,97	0,98	0,02
RT2	86,31	4,20	2,53	2,35	2,57	1,11	0,82	0,1

The sample after sintering consists mainly of Al₂O₃ (86.14 wt%) and P₂O₅ (4.37 wt%), which is a component of the anti-wetting agent AlPO₄. SiO₂, TiO₂ and MgO are between 2.29 and 2.59 wt.%, Fe₂O₃ is 1.01 wt.%. The loss on ignition is 0.18 wt.%.

After the trials at 950 °C in steam (MT2-1) and at 1350 °C in air (RT2), the composition remains largely unchanged. The maximum deviations are ± 0.4 wt.% for MT2-1 and ± 0.2 wt.% for RT2. The annealing losses are 0.14 and 0.10 wt.%, respectively.

After removal at 1350 °C in water vapor (MT2-2) and hydrogen-containing atmosphere (MT2-4), the P₂O₅ content decreases to 3.84 wt.% (-12%) and 3.45 wt.% (-21%) respectively compared to the sample after sintering. The relative Al₂O₃ content increases to 87.55 wt.% (+1.6%) for MT2-2 and 87.26 wt.% (+1.3%) for MT2-4. SiO₂, TiO₂, MgO and Fe₂O₃ remain largely unchanged. Both samples exhibit lower values than the zero sample, MT2-1 and RT2, with a loss on ignition of at most 0.02 wt%.

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Phase Analysis (XRD)

The phase composition of the sample after sintering as well as the main and reference experiments was investigated using semi-quantitative evaluation of the peak intensities (Table 35). Areas Z1 and Z3 of the main trials are considered separately. Main phases are marked with „+++“, secondary phases with „++“ or „+“, traces with „-“ and undetectable phases with „0“.

Table 35: Phase composition of the exposed samples relative to sample after sintering

Sample	Corundum (Al ₂ O ₃)	Aluminum phosphate (AlPO ₄)	Magnesium phosphate (Mg ₃ (P ₂ O ₈))	Titanium dioxide (TiO ₂)	Mullite (Al ₆ Si ₂ O ₁₃)	Berlinite (AlPO ₄)
MT2-0	+++	++	+	+	-	0
MT2-1- Z1	+++	++	+	++	-	0
MT2-1- Z3	+++	++	+	++	-	0
MT2-2- Z1	+++	-	+	+	0	-
MT2-2- Z3	+++	-	+	+	0	0
MT2-3- Z1	+++	++	+	++	-	0
MT2-3- Z3	+++	++	+	++	-	0
MT2-4- Z1	+++	-	+	+	0	0
MT2-4- Z3	+++	-	+	+	0	0
RT1	+++	++	+	++	-	0
RT2	+++	-	+	+	0	-

In the sample after sintering (MT2-0), corundum is the main phase. AlPO₄, Mg₃(P₂O₈) and TiO₂ exist as second phases, with AlPO₄ having the highest peak intensity. Mullite can be detected in trace amounts.

After the test at 950 °C, corundum remains the main phase in all trials (MT2-1, MT2-3, RT1). AlPO₄ and Mg₃(P₂O₈) remain unchanged as minor phases and mullite as a trace phase. The peak intensity of TiO₂ increases compared to the zero sample in both sample ranges as well as in the reference experiment, without changing its classification as a side phase. No differences are apparent between Z1 and Z3.

At 1350 °C, corundum remains the main phase in all trials (MT2-2, MT2-4, RT2). Its peak intensity is higher than that of the sample after sintering and the samples outsourced at 950 °C. The peak intensity of AlPO₄ decreases in all atmospheres. The phase is only detectable in trace amounts at MT2-2, MT2-4, and RT2. Traces of berlinite also occur at MT2-2-Z1 and RT2, which are absent in the sample after sintering and the samples deposited at 950 °C. Mg₃(P₂O₈) remains unchanged as a secondary phase. TiO₂ is back at the intensity level of the sample after sintering. Mullite is no longer detectable at 1350 °C after all tests.

8.4 Conclusion

The investigations show that exposure at 950 °C causes no pronounced changes in the barium sulfate-rich material. Exposure at 1350 °C leads to more distinct changes, which are strongly position-dependent. An inhomogeneous temperature distribution within the furnace is a plausible explanation and should be taken into account in future experiments. Measuring the temperatures prevailing at each position with an inserted thermocouple proved to be of limited practicability. Process temperature control rings could be a suitable alternative for recording the thermal load. In the front sections of the bars exposed at 1350 °C in the front

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position, under both steam- and hydrogen-containing atmospheres, the formation of a surface layer was observed. The corresponding examination of the rear bars is still pending. Further investigation of these regions appears worthwhile to determine whether the observation results from position dependent effects within the gas flow or from the inhomogeneous temperature distribution inside the furnace tube. Under thermal exposure, the deviations in Young's modulus measured at room temperature largely level out as a result of the aging.

The AlPO_4 -containing material, in contrast, shows a pronounced temperature dependence. At 950 °C, mass, open porosity and phase composition remain nearly unchanged. At 1350 °C in the steam-containing atmospheres, it shows a significant mass loss, an increase in open porosity and a decomposition of AlPO_4 , during which phosphorus volatilizes and corundum remains. The comparison with the reference shows that part of this degradation is caused by temperature alone, as the reference also undergoes phase degradation. The more severe damage observed additionally in the steam-containing atmospheres is attributed to the gas flow promoting the removal of volatile decomposition products. Mass loss, increase in open porosity and phase degradation are comparable in both steam-containing atmospheres. The hydrogen-containing atmosphere, however, has a stronger reducing effect. This is evident in a higher phosphorus loss, a more pronounced reduction of titanium and a slightly darker discoloration of the samples.

The two temperatures represent different loads: 950 °C is a moderate load, whereas 1350 °C was deliberately chosen as a limiting case, 50 °C below the maximum service temperature of 1400 °C specified by the manufacturer. The AlPO_4 -containing material therefore remains largely stable at the moderate temperature. Near its upper service limit, the decomposition of AlPO_4 causes it to lose both its phosphate bond and its protective effect.

8.5 References

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9 Main conclusions for aluminium work package

The following conclusions are a summary of the key points that have been shown on the different conclusions on each of the demonstrators, focusing on the main points and the overall trend of the results, as some of them may have obtained contradictory results.

These tests have been limited in time but have given a very good overall impression of the capabilities that hydrogen as a fuel can give to the aluminium producers:

- **Natural gas replacement:** Hydrogen as a substitute of natural gas is a completely viable alternative for using in the existing equipment and installations with minimal adaptation when compared with other renewable energy sources. The thermal performance and energy consumption when using hydrogen has shown that the results are equal or better than when using natural gas, with the overall energy consumption being a bit lower when using hydrogen in some cases due to the higher heat transference of the water vapour molecules present in the hydrogen combustion.
- **Safety:** From the safety point of view, that was one of the main risks of the project, all the tests have been completed with no incidents, demonstrating that the use of hydrogen can be safe when taking the adequate measures.
- **Aluminium quality:** The final quality of the aluminium, a critical key performance indicator (as a lower quality aluminium could hinder the usage of hydrogen), has also been equal or very similar to the quality of the aluminium when using natural gas. The only outstanding point would be the higher presence of hydrogen in the aluminium itself, but that is an issue already solved in the cast houses thanks to the degasser equipment present, so no really critical point has appeared in terms of quality.
- **Emissions:** As expected, using hydrogen provides a massive reduction or complete elimination of the CO₂ emissions, with is the main point of the project, eliminating the greenhouse gas emissions. However, as a side effect of using hydrogen there is an upwards trend in Nox emissions and special attention must be paid to handling it, sealing the furnaces to ensure no air infiltration and working with low Nox burners.
- **Simulations:** Simulations have proven to be a highly reliable tool that can determine potential unwanted effects and help correct them before they appear or are carried out. The models have been successfully validated by the real world results and will allow companies to develop reliable solutions when switching fuels in the existing or new equipment to other renewable energies.

10 Policy recommendations

Based also on the results, the following recommendations are given for a more efficient decarbonization of the aluminium industry in the future:

- **Accelerate funding for gas generation hubs:** Hydrogen has proven to be a highly viable fuel but the current price when compared to natural gas does not make it viable in the long term for most of the aluminium producers. Incentivizing the creation of generation centers for hydrogen or other similar green gases that can be used with the existing equipment is critical for achieving a competitive gas that can be the substitute of the natural gas for the next years.
- **Revise Nox emission metrics:** Current Nox emission measurements are not in line with the industry trend of high heat recuperation or switching to hydrogen, as employing both technologies will lead with the current measurement standard used in the EU to higher NOx emissions. This will make difficult to progress in both fields as the current NOx limits are progressively reduced. The article that was originated within the project “NOx Emission Limits in a Fuel-Flexible and Defossilized Industry—Quo Vadis?” explains more in details the current challenges facing the NOx emissions.

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