PUBLIC SUMMARY

Explore the use of sustainable hydrogen as a fuel for industrial heating processes

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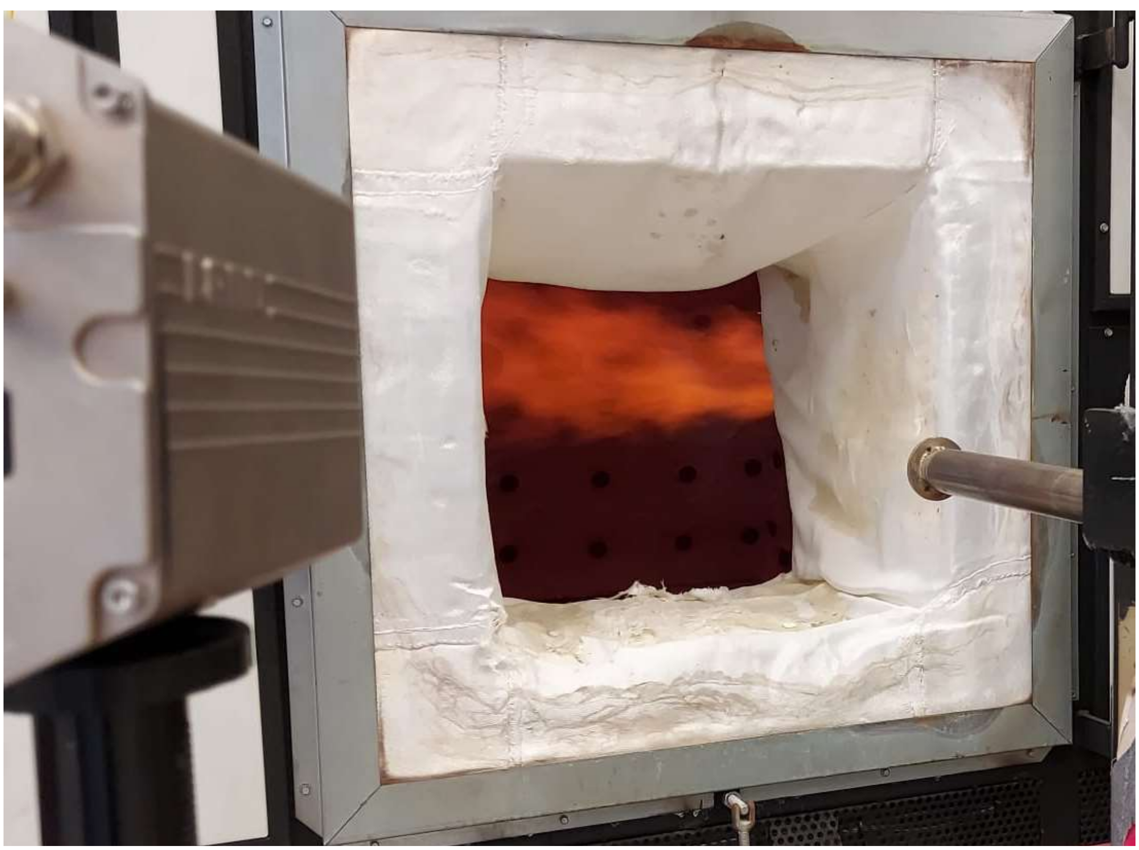

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Cover picture: IR camera (left) and radiation flux sensor (right) measuring hydrogen flame in high temperature kiln

SAMENVATTING

Industriële samenwerking om met waterstof koolstof uitstoot te verlagen

Energie-intensieve industrieën staan voor een grote uitdaging om de koolstof uitstoot van hun verhittingsprocessen te verlagen. Deze sector omvat fabrikanten van glas, asfalt, metaal, raffinage, chemicaliën, voedsel en keramiek. Om de koolstofintensiteit van hun industriële processen te verminderen, wordt overwogen om aardgas te vervangen door groene (en blauwe) waterstof.

Het grote voordeel van waterstof als brandstof voor verwarmingsprocessen is dat ovens, ketels en fornuizen die worden gebruikt voor productfabricage en warmtebehandeling zelf niet drastisch hoeven te worden omgebouwd bij het overschakelen naar waterstof wat resulteert in 'beperkte' investeringskosten. De verbrandingseigenschappen van waterstof wijken echter af van die van aardgas. Het is om deze reden noodzakelijk fundamenteel inzicht te verkrijgen op de invloed van deze veranderingen in verbrandingseigenschappen op verbrandingsprestaties en warmteoverdrachtsprocessen. Met deze inzichten kunnen industriële processen goed worden (her)ontworpen. Het ontwikkelen van kennis op dit gebied is essentieel voor een succesvolle transitie naar een waterstofeconomie voor de hoge temperatuurindustrie.

Begin 2020 zijn DNV, CelSian en Stork Thermeq samen met 40 partners een project gestart om het gebruik van duurzame waterstof als brandstof voor industriële verwarmingsprocessen mogelijk te maken. Dit onderzoeks- en testprogramma van twee en een half jaar leverde belangrijke bouwstenen voor de uitrol van de duurzame waterstofwaardeketen en de ontwikkeling van gerelateerde verbrandingstechnologie. Het project heeft belangrijke inzichten opgeleverd over verbrandingsgedrag, warmteoverdracht, emissiebeperkende strategieën en operationele veiligheid.

Binnen het project zijn de prestaties van vijf commercieel verkrijgbare industriële aardgasbranders die worden gebruikt in directe en indirecte verwarmingsprocessen getest met waterstof/aardgasmengsels variërend van 0-100% waterstof. Om optimale verbrandingsprestaties te behouden, is een brandstof adaptief brander-besturingssysteem toegepast. Binnen het project zijn de volgende aspecten bestudeerd: verbrandingseigenschappen, warmteoverdracht, warmteverdeling, oververhitting van de brander en emissies. De laboratorium testen zijn aangevuld met CFD-modellering. Daarnaast is binnen het project een nieuw waterstof-oxyfuel verbrandingssysteem voor stoomproductie ontwikkeld en gedemonstreerd. Dit systeem maakt gebruik van mengsels van waterstof/zuurstof/waterdamp om te zorgen voor NO_x-emissie vrije verbranding voor lage temperatuursprocessen. Voor hoge temperatuursprocessen, zoals het smelten van glas zijn binnen het project de prestaties en warmteoverdracht van een aardgas-oxyfuel-brander bestudeerd voor aardgas/waterstofmengsels. Verder inzichten zijn verkregen op het gebied van: op welke wijze waterstof/aardgas en zuurstof (of lucht) mengsels veilig kunnen worden toegepast op industriële schaal, hoe waterstofvlammen kunnen worden bewaakt, hoe waterstofvlammen kunnen worden gedetecteerd en beveiligd, hoe emissies zoals NO_x in waterstof/zuurstofvlammen kunnen worden gemeten en welke veranderingen in warmteoverdracht zijn te verwachten bij het overschakelen van aardgas naar waterstofverbranding.

Samenvatting van de belangrijkste bevindingen

1 Voor alle vijf geteste aardgasbranders, inclusief de oxyfuel-brander, zijn goede en veilige verbrandingsprestaties waargenomen over het hele scala van bestudeerde waterstof/aardgasmengsels, bij toepassing van een brandstof adaptief regelsysteem dat het thermisch vermogen en de luchtfactor constant houdt. In het algemeen is op basis van de resultaten geconcludeerd dat de toevoeging van waterstof resulteert in snellere verbranding dichter bij de brander, wat de integriteit (levensduur) van het vuurvaste materiaal nabij de brander, het branderblok of (indien van toepassing) de keramische buis kan beïnvloeden. De waargenomen veranderingen in vlamstructuur die ontstaan door toevoeging van waterstof zijn echter afhankelijk van het gebruikte brandertype. Bij de onderzochte branders heeft de verschuiving van de hete vlamzone dichter naar de brander niet geleid tot oververhitting van de branderkop. Verder onderzoek wordt aanbevolen naar het verschil in levensduur van vuurvaste materialen.

2 Metingen binnen het project laten een verhoogde warmteoverdracht zien naar de koelwatervloeren die in de oven zijn geïnstalleerd bij het volledig overschakelen van aardgas naar waterstof. De mate van verandering in de warmteoverdracht is echter afhankelijk van het type brander. Er zijn geen grote veranderingen waargenomen in de warmteverdeling in de oven waargenomen voor de geteste branders. De gemeten veranderingen in warmteoverdracht en warmteverdeling zijn over het algemeen goed voorspelbaar door de CFD-berekeningen.

3 Er is gebleken dat voor het merendeel van de geteste branders een toename van de NO_x-emissie bij waterstoftoevoeging optreedt. De mate van veranderingen in NO_x-emissies bij toevoeging van waterstof zijn sterk afhankelijk van het type brander. Bij de meeste branders is een exponentiële toename van de NO_x-emissie geconstateerd bij toevoeging van waterstof aan aardgas. De geteste zuurstofbrander produceerde echter minder NO_x bij het overschakelen op pure waterstofverbranding. Voor lage temperatuur processen, zoals stoom- en warmwaterproductie, werd de waargenomen NO_x-toename met succes verminderd door externe rookgasrecirculatie toe te passen. Voor de industriële branders die in de hoge temperatuur oven zijn getest, is het echter nog een uitdaging om de NO_x-emissie te verminderen, aangezien de rookgastemperaturen vaak te hoog zijn voor externe rookgasrecirculatie. Het is aan te bevelen om in een vervolgstudie mogelijke NO_x-reducerende maatregelen voor industriële processen op hoge temperatuur verder te onderzoeken, bijvoorbeeld door het branderontwerp te optimaliseren. De noodzakelijke wijzigingen in het ontwerp zijn sterk afhankelijk van het gebruikte brandertype. In het algemeen moet het nieuwe ontwerp (langzamer) mengen van brandstof en lucht in een later stadium in het verbrandingsproces mogelijk maken, zorgen voor een betere afvoer van rookgas en/of een kortere verblijftijd. Dit kan bijvoorbeeld door de snelheden van de brandstof- en lucht te veranderen en meer interne rookgasrecirculatie te creëren, of door de positie van de brandstoflans te veranderen.

4 Om bij het gebruik van waterstof als brandstof emissies te monitoren, de vlamstructuur te visualiseren en het verbrandingsproces te bewaken, zijn binnen het project detectietechnieken ontwikkeld en getest. Dit omvatte een veiligheidsmonitoringsysteem - ontwikkeld, gebouwd en getest als onderdeel van het project - om de werking van verbrandingsinstallaties mogelijk te maken zonder continu toezicht door een operator, vergelijkbaar met de industriële praktijk. Om waterstofvlammen te detecteren en te visualiseren, wat belangrijk is voor veiligheid, R&D en operationele redenen, ontwikkelde het bedrijf LAND een prototype infrarood camera voor het project. Deze camera is met succes getest. Verder is in het project de CelSian IR-laser opnieuw gekalibreerd voor waterstofverbranding voor in-situ temperatuur-, CO-, H_2O- en O_2-metingen. In het algemeen zijn goede prestaties vastgesteld voor de IR-laser voor alle bestudeerde aardgas/H_2-brandstofmengsels, voor zowel lucht- als zuurstofverbranding. Voor zuivere waterstof was de H_2O-concentratie in het vlamfront echter te hoog. Daarom is her-kalibratie voor H_2O aan te bevelen. Hoewel H_2/O_2-vlammen alleen water en zuurstof als rookgassen produceren, kunnen de rookgassen stikstof bevatten als gevolg van lucht-inlek en onzuiverheden zoals stikstof in de waterstof- en zuurstoftoevoer, wat resulteert in NO_x-emissies die nauwkeurig moeten worden gemeten. In dit project is een NO_x emissie meetprocedure voor zuivere H_2/O_2 vlammen ontwikkeld en getest.

5 Bij het gebruik van H_2/O_2 (oxyfuel) mengsels voor retrofit in industriële ketels, hebben de testen aangetoond dat dit mogelijk is door grote hoeveelheden rookgasrecirculatie (voornamelijk H_2O) toe te passen. Dit verlaagt de vlamtemperaturen vergelijkbaar met het gebruik van conventionele aardgas- en/of waterstofverbranding met omgevingslucht. Bovendien helpt dit om de convectieve warmteoverdracht te verbeteren. De testen hebben aangetoond dat het concept succesvol blijft functioneren bij het overschakelen van een conventionele bedrijfsmodus naar een volledig zuurstofbrandstofmengsel en vice versa. Tijdens oxyfuel-bedrijf van de installatie daalde de NO_x-emissie tot bijna nul ppm. Daarnaast is het systeem met succes beveiligd met in de handel verkrijgbare dual cell vlamscanners. Aanvullende veiligheidsvoorzieningen zorgden voor een geschikt operationeel werkgebied, door in-situ meting van O_2 en het voorkomen / detecteren van condensatie van water.

EXECUTIVE SUMMARY

Industrial collaboration to lower carbon intensity with hydrogen

Energy-intensive industries are facing a major challenge to decarbonize their heating processes. This includes manufacturers of glass, asphalt, metal, refining, chemicals, food, and ceramics. To reduce the carbon intensity of their industrial processes, these manufacturers are considering replacing natural gas with green (and blue) hydrogen.

The major advantage to use hydrogen as fuel for heating processes is that the kilns, boilers, and furnaces used for product manufacture and heat treatment themselves do not need to be changed drastically when switching fuels, resulting in only limited investment costs. However, various combustion characteristics of hydrogen deviate from the combustion characteristics of natural gas. Therefore, this fuel transformation requires fundamental understanding of the impact of these deviations on combustion performance and heat transfer processes in order to (re-)design industrial processes properly. Developing knowledge in these areas is essential for a successful transition to a hydrogen economy for the high temperature industry.

Starting early 2020, together with 40 partners, DNV, CelSian and Stork Thermeq explored the use of sustainable hydrogen as a fuel for industrial heating processes. This two and half year research and testing program provided important building blocks for the roll-out of the sustainable hydrogen value chain and the development of related combustion technology. The project delivered important insights and learnings on combustion behaviour, heat transfer, emission mitigating strategies and operational safety needed for a gradual transition from natural gas to hydrogen.

The project tested the performance of five commercially available industrial natural gas burners used in direct- and indirect heating processes, using hydrogen/natural gas blends ranging from 0-100% hydrogen. To maintain optimal combustion performance, a fuel adaptive burner control system was coupled to the burner management systems. During burner tests, the project experimentally studied and analysed changes in combustion properties, heat transfer, heat distribution, overheating of the burner, kiln atmosphere, and emissions as hydrogen was added to natural gas. The analysis is supplemented by performing CFD modelling. In addition, the project developed and demonstrated a novel hydrogen oxyfuel combustion system for steam production. This system uses hydrogen/oxidizer/water vapor mixtures to ensure zero NO_x emissions during combustion for low temperature processes. For high temperature processes, the project studied the performance and heat transfer of a natural gas oxyfuel burner, typically used for glass melting, using natural gas/hydrogen blends. Furthermore, the project addressed how to safely supply hydrogen/natural gas and oxygen (or air), how to monitor hydrogen flames, how to detect and safeguard hydrogen flames, how to measure emissions such as NO_x in hydrogen/oxygen flames, and what changes in heat transfer to expect when switching from natural gas to hydrogen combustion.

Summary of key findings and learnings

1 For all five natural gas burners tested, including the oxyfuel burner, the project observed **good and safe combustion performance** over the entire range of hydrogen/natural gas blends studied, when applying a fuel adaptive control system that keeps the thermal power and air factor constant. Generally, the project observed that the addition of hydrogen results in combustion closer to the burner, which may impact the integrity (lifetime) of the refractory material near the burner, the burner block, or (if applicable) the ceramic tube. However, the

exact changes in flame structure following the addition of hydrogen depends on the burner type used. For the burners studied, the shift of the hot flame zone closer to the burner did not result in overheating of the burner head. The project recommends further study on the difference in the **lifetime of refractory materials** when switching to hydrogen combustion for high temperature processes.

2 Measurements from the project show **increased heat transfer** – to the cooling water floors installed in the furnace –when switching completely from natural gas to hydrogen combustion when keeping the burner power and air factor constant. However, the degree of change in the heat transfer depends on the burner type. The project also tested the addition of hydrogen to natural gas combustion and its impact on heat distribution. These changes depend upon the burner type used, but in general the project found **no major changes in the heat distribution** in the furnace. The changes observed in heat transfer and heat distribution were generally well captured by the CFD calculations.

3 The tests found that an **increase in NO_x emissions** upon hydrogen addition can be an issue for most of the tested burners. The qualitative and quantitative changes in NO_x emissions upon the addition of hydrogen strongly depends on the burner type. For most of the burners, the project observed an exponential increase in NO_x emissions when hydrogen is added to natural gas. However, the tested oxyfuel burner produced less NO_x when switching to pure hydrogen combustion. For low temperature processes, such as steam and hot water production, the observed NO_x increase was successfully reduced by applying external flue gas recirculation. However, for the industrial burners tested in the high temperature furnace, reducing NO_x emissions is still a challenge to be solved, since the flue gas temperatures are often too high for external flue gas recirculation. The project recommends to further investigate possible **NO_x mitigating measures** for high temperature industrial processes in a follow-up study, for example by optimizing the burner design. The necessary changes in the design depend strongly upon the burner type used. In general, the new design should enable (slower) mixing of fuel and air at a later stage in the combustion process, provide improved flue gas entrainment, and/or allow a shorter residence time. This is possible by, for example, changing the velocities of the fuel and air jets and creating more internal flue gas recirculation, or by changing the position of the fuel lance.

4 To monitor emissions, visualize the flame structure, and safeguard the combustion process, the project developed and tested **detection techniques for the use of hydrogen as a fuel**. This included a safety monitoring system – developed, built, and tested as part of the project – to enable the operation of combustion installations without continuous supervision by an operator, similar to industrial procedures in the field. To detect and visualize hydrogen flames, which is important for safety, R&D, and operational reasons, the company LAND developed a prototype infrared Land camera for the project. This camera was tested successfully. Furthermore, the project used the CelSian IR laser – recalibrated for hydrogen combustion – for in-situ temperature, CO, H_2O and O_2 measurements. Generally, the project observed good performance of the IR laser for all studied natural gas/H_2 fuel blends, for both air and oxyfuel combustion. However, for pure hydrogen the H_2O concentration in the flame front was too high. Therefore, the project recommends recalibration for H_2O. Although H_2/O_2 flames only produce water and oxygen as flue gases, the flue gases might contain nitrogen that is present from air ingress and impurities such as nitrogen present in the hydrogen and oxygen supply, resulting in NO_x emissions which should be measured accurately. In this project a **NO_x emission measurement procedure for pure H_2/O_2 flames** developed and tested.

5 When utilizing **H_2/O_2 (oxyfuel)** mixtures for retrofitting in industrial boilers, the tests demonstrated that this is possible by applying large amounts of **flue gas (mainly H_2O) recirculation**. This reduces the flame temperatures similar to when using conventional natural gas and/or hydrogen combustion with ambient air. Additionally, this helps to minimize the effect of the reduced amount of flue gasses passing through the convective heat transfer areas of the boiler by the omission of nitrogen. These tests demonstrated the concept of changing from a conventional operating mode to full oxyfuel mixture operation and vice versa. During oxyfuel operation of the installation, NO_x emissions declined to near-zero part per million (ppm). It was possible to

safeguard the burner flame using commercially available dual cell flame scanners, and additional safeguarding provisions ensured a suitable operating window, though in-situ measuring of O_2 and preventing/detecting condensation.

1 INTRODUCTION

1.1 Decarbonizing the energy-intensive industry

The energy-intensive industry faces the major challenge of drastically reducing the carbon intensity of manufacturing processes to meet current and future climate agreements. A substantial part of the CO_2 emissions from these industries is generated by burning fossil fuels for heating processes. As an example, in the Netherlands more than 200 petajoules (PJ) of natural gas energy is used in heating processes in the industry. At present, there is no technology available that enables large-scale energy savings and decarbonization for this group of industrial processes. The CO_2 emissions reduction target set by the Dutch government (49 percent reduction in 2030 relative to the 1990 level) necessitates far-reaching measures for the industry. The clear challenge is not only to reduce the carbon emissions from the industry, but also to maintain the long-term competitive position of the energy-intensive industry, for sustainable growth and employment, all without an increase in the emissions of greenhouse gases.

A sustainable route to reduce the carbon intensity for industrial heating processes is to replace natural gas with green hydrogen. The major advantage to use hydrogen as fuel for heating processes is that the kilns, boilers, and furnaces used for product manufacture and heat treatment themselves do not need to be changed drastically when switching fuels, resulting in only limited investment costs (CAPEX). In contrast, the alternative of electric heating often requires a complete redesign of the heating part of the production process and, moreover, is often not technically feasible, since interaction with combustion products (reducing/oxidizing atmosphere) is needed for production. In this case, the industry will be faced with large investments and, more importantly, with a large and dedicated program of research and development – to assess the feasibility for individual industrial processes and to develop feasible technologies for implementation. In addition, the natural gas grid is already connected to the industry and can be used to transport hydrogen, while enabling the use of electricity requires large investments in infrastructure, which is both time consuming (delaying process conversion) and economically unattractive.

Figure 1.1 : Green hydrogen: a sustainable route to decarbonize industry

1.2 Hydrogen for industrial heating processes

Industrial heating processes can roughly be divided into indirect- and direct heating. Indirect heating is when the substance to be heated, referred to as the load, is separated from the combustion products, for example by heating tubes through which a chemical feedstock flows. In contrast, direct heating exposes the product directly to the flame and/or combustion products in an industrial furnace (or kiln). Changing the fuel composition alters the combustion and can change the properties of the furnace atmosphere, potentially (adversely) affecting product quality in these direct-heating processes. Heating of the product itself occurs by two main physical processes: convection and radiative heat transfer. Heat transfer from the flame and combustion products is strongly dependent upon the type of fuel burned. For example, hydrogen combustion produces non-luminous flames since it does not contain any carbon to form soot. As a result, hydrogen flames have different radiative heat transfer properties than hydrocarbon flames. Many heating processes, such as bulk glass melting, depend upon intense radiative heat transfer. Changes in the radiative heat transfer arising from a different fuel composition can affect process efficiency and product quality.

Figure 1.2 : High temperature glass production with natural gas

In the initial phase of the energy transition, it is unlikely that there always will be sufficient hydrogen available to satisfy the entire industrial energy demand, whose processes usually run continuously (24/7) throughout the year. To avoid shutting the production process down due to lack of (pure hydrogen) fuel, an attractive solution is to apply burner systems that can, without manual adjustment, flexibly utilize the full mix of fuel compositions: 100% hydrogen, 100% natural gas and all mixtures of hydrogen and natural gas in between. The major economic advantage of such a system is that it offers robust fuel flexibility with only limited investment: the same burner system can be used throughout the transition, supplied initially with varying natural/gas hydrogen mixtures, and afterwards with pure hydrogen when the supply has risen to the challenge.

Since the combustion properties of hydrogen substantially differ from those of natural gas – having much higher burning velocity and diffusion rates, and a much lower calorific value – not all burners will be able to accept the wide variety of fuel composition without flame instability, burner overheating, or unacceptable loss of thermal input. An additional issue that needs to be addressed is the increase in flame temperature that occurs when moving in composition from pure natural gas towards pure hydrogen, which can result in an increase in the NO_x formation above the current (and future) regulatory limits.

1.3 Research program – Industry consortium

The challenge for the transition of direct and indirect heating processes to a carbon-free, hydrogen-fuelled, future is to maintain (or improve) product quality and to optimize efficiency, while keeping NO_x emissions within the prescribed limits for the range of fuel compositions encountered in the transition: from natural gas to pure hydrogen. To meet these challenges, it is essential to tailor the heat transfer (including footprint), the composition of the kiln atmosphere, and NO_x mitigating strategies, for the different product classes, combined with a well-functioning burner system. As there is hardly any experimental data on all these aspects, applied research is necessary to facilitate this transition. At present, no retrofit burner technology is available that can handle the combustion of varying natural gas/hydrogen mixtures (0-100% hydrogen) while maintaining efficiency and low NO_x emissions. Additionally, during the electrolysis process to produce hydrogen from wind and solar energy, oxygen is produced in large quantities (1 mole H_2: ½ mole O_2). Oxyfuel combustion has the advantage of high efficiency and NO_x emissions, making it an attractive combustion technology. For high temperature processes, such as melting glass, oxyfuel combustion using natural gas as a fuel is commonly used, but much is unknown regarding $CH_4/H_2/O_2$ combustion. This knowledge is essential for a successful transition to a hydrogen economy for the high-temperature industry. Furthermore, no oxyfuel combustion systems are available for low temperature oxyfuel combustion, so these processes cannot benefit yet from the advantages of oxyfuel combustion.

Early 2020 DNV and Celsian initiated a unique industry research program to explore the introduction of hydrogen as a fuel for industrial use, aiming to contribute fundamental improvements to existing industrial heating processes to make the gradual transition from natural gas to hydrogen fast and cost-efficiently. The above described research topics were transferred in a set of research questions listed in section 1.4.

1.4 Summary of research questions

Combustion performance	• What percentage of hydrogen is allowed in methane, while maintaining good burner performance by using commercially available natural gas burners? • Can we safely add hydrogen to natural gas when using oxyfuel combustion? And how is this best achieved? • What changes in combustion performance occur when hydrogen is added to the fuel mix? • What are the effects on emissions (NO_x, CO, H_2 in flue gas)? • Does existing flame detection (flame guarding) systems need to be replaced, and if so do commercially available flame guarding systems work properly? • Are there any effects or changes in flame shape when adding hydrogen to natural gas? • Can we reduce NO_x emissions by applying measures such as external flue gas recirculation? • Is it possible to develop a zero NO_x emissions hydrogen oxyfuel system for low-temperature processes?
Measurement & detection techniques	• Are traditional measurement and detection techniques available on the market suitable to determine combustion performance? • Existing technologies to visualize the flame structure often use CO_2 emission lines. Since hydrogen flames do not contain CO_2,. Can we use recalibrated IR cameras (using the H_2O spectral lines for H_2/air flames) to visualize natural gas/H_2/air and natural gas/H_2/O_2 flames? • Can we determine H_2 in the flue gas in the case of incomplete combustion? • Are optical in-situ measurements suitable to measure the temperature, CO, H_2O and O_2 in the flue gases of CH_4/H_2/O_2 flames? • How can we measure NO_x emissions on a dry basis (no water vapour in the sample gas) in pure hydrogen flames, if the only products in the flue gas are the excess O_2 and a very small amount of NO_x?
Heat transfer (CFD) modelling	• Does the heat transfer (convection + radiation) change upon hydrogen addition at constant burner power? • Does the temperature distribution in the furnace change upon hydrogen addition? • Can we predict the changes in combustion performance and heat transfer by using CFD analyses? • What is the impact of air preheating on an end port fired container glass furnace when using hydrogen as a fuel? • What is the impact of hydrogen blending to natural gas on the burner tip and burner block.

2 SELECTED BURNERS & CONDUCTED TEST PROGRAM

The test program aimed to deliver insightful experimental data, on how commercial available burner systems for indirect- and direct heating respond during combustion to different levels of hydrogen. Many different types of burners are used in industrial production processes, each with their own characteristic combustion properties. To get a good picture of the impact of hydrogen addition to natural gas for different burner technologies, five different burner systems were selected for investigation.

The five studied burner systems are presented in Table 2.1. Burner 1 was tested in a 450 kW hot water boiler and burners no. 2-5 were tested in a 500 kW high temperature furnace at DNV. The details of the test set-up are described in Chapter 3. Furthermore, a novel hydrogen oxyfuel system for low temperature processes was developed and tested in this project by Stork Thermeq in cooperation with DNV (see section 4.6)

Table 2.1: Burners selected for hydrogen/natural gas tests

Burner no.	Type of burner	Industrial application
1	Forced draught burner	Hot water and steam production
2	Swirl burner	Steel production
3	High velocity burner	Ceramic industry
4	Hot air burner	Glass production
5	Oxyfuel burner (flat flame)	Glass production
Novel oxyfuel combustion system	Swirl burner	Hot water and steam production

The performance of the burners was studied using different hydrogen/natural gas blends. During these tests, hydrogen was added in steps of about 10 vol% up to 100 vol% hydrogen at different burner loads, depending on the burner type studied. As a NO_x mitigating measure, the air factor (λ) was changed. As a second strategy, external flue recirculation was applied for the tests in the boiler system using burner no. 1. For the test in the furnace, external flue gas recirculation was complex since the flue gases had temperatures above 650 °C. As an alternative, nitrogen was added to several natural gas/H_2 blends to mimic flue gas recirculation. The experiments for burners no.2-5 were performed at furnace temperatures ranging from about 600-1200 °C. The furnace temperature for the experiments used a cooling floor (see Figure 3.3) to mimic heat transfer to the product to reduce the temperature to about 600-750 °C. The burner test parameter variation is presented in Table 2.2.

Figure 2.1 Oxyfuel burner - burner no. 5 installed in kiln

Table 2.2: General overview parameter variation used in the burner tests

Parameter variation	
Hydrogen/natural gas blends	0-100% vol% H_2 in natural gas (gradual increases is H_2 percentage with steps ranging from 10-20 vol% H_2)
Air preheating[1]	0-450 °C using different H_2/natural gas blends (Gradual increase in the combustion air temperature)
Burner load variation	Different thermal inputs for example low, mid, high burner loads using different natural gas/H_2 blends (ranging from 100-450 kW depending upon the burner type)
Testing NO_x mitigating measures	Varying air factor (λ=1-1.5), addition of N_2 blending to natural gas/H_2[2] and applying flue gas recirculation[3]
Temperature furnace[4]	600-1200 °C Experiments were performed with and without cooling floor to determine the heat transfer efficiency.
[1] Burner 2 and 4 [2] Burner 2, 3, 4, 5 [3] Burner 1 [4] Burner 2, 3, 4, 5	

During the tests the following parameters were measured:

- The combustion performance of the burner:
  - Burner tip temperature
  - Flame length
  - Emissions in the flue gases, such as H_2, CH_4, CO, CO_2, NO, NO_2, and O_2
- Temperature of the hot combustion gases, both in the kiln and in the flue gases at the exit of the kiln.
- Changes in flame structure using an IR camera.
- Heat transfer to the cooling floors, by measuring the inlet and outlet water temperature and the water flow.

The details of the burner tests can be found in the confidential reports [1-5].

3 TEST FACILITIES & BURNER CONTROL SYSTEM

3.1 Experimental test facilities

The project performed burner performance tests for low temperature systems (in a boiler) and high temperature systems (in a furnace). For low temperature processes, the project developed, built, and tested a proof of principle for oxyfuel combustion with zero NO_x emissions. For high temperature processes the tests included hydrogen/oxygen combustion by using a natural gas oxyfuel burner. The experimental test program was carried out at the DNV Technology Center in Groningen (NL), where a wide range of dedicated test facilities and state of the are measurement technologies are available.

The performance tests for burner no. 1 (see Table 2.1), which is used for low temperature indirect heating processes, were performed in a 450kW hot water boiler system presented in Figure 3.1. The furnace presented in Figure 3.2 was used to test the burners no. 2-5 for high temperature direct heating processes such as the production of glass, steel and ceramics. The test facilities were equipped with quartz windows that allowed us to visualize the flame structure. Flue gas analysers were installed to monitor the CO, CO_2, CH_4, C_xH_y, NO and NO_2 emissions. In the furnace, an in-situ laser was installed that allowed us to measure the H_2O, CO, O_2 and temperature inside the kiln. For flame visualization a CCD camera and a prototype LAND IR camera were used to detect the flame structure. The original IR camara detected the flame based on CO_2 lines. However, hydrogen does not produce CO_2 and thus cannot be observed with the original IR camera. Upon combustion both hydrogen and natural gas produce water, and for this reason, the LAND IR prototype camera visualized the flame structure based on the water vapour emission lines in the infrared region.

Several of the natural burners tested contain flame guarding systems utilizing an ionization probe that monitors the continuous presence of the flame by measuring the ionization current through the flame. This is in case the current falls below a certain threshold value the boiler shuts itself off. When burning only hydrogen, a weak ionization current signal can be detected, which is well below the threshold value. Therefore, the original flame guarding systems of these burners were replaced by a flame detector that measures the UV radiation emitted by the flame. These UV flame detection sensors are developed for natural gas and were tested in this project for natural gas/hydrogen combustion.

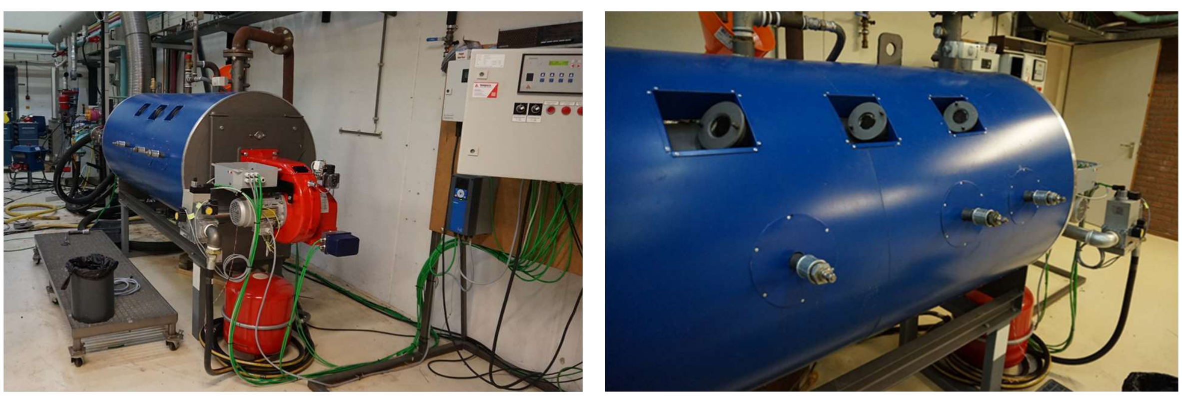


Figure 3.1 : 450 kW boiler and forced draught burner. The boiler has three quartz windows for flame structure observation.

The hydrogen and natural gas (or methane) were supplied via a custom-built fuel supply system equipped with calibrated Bronkhorst mass flow meters and flow controllers to measure and set the individual flows. The air was supplied by a fan. For the oxyfuel tests a dedicated (safe) oxygen supply system was designed, built, and tested within this project (see Figure 3.4). The supply system was connected to the burner management and flow control system (BMS) that assures safe start-up, operation, and shutdown of the burner. As the oxyfuel burner is not equipped with a BMS, a system was designed and built to provide a dedicated BMS for tests on this oxyfuel burner system.

Figure 3.2: Analysers for detecting NO_x, and O_2 in the flue gas (left). In-situ IR laser for detecting O_2, CO, water and the temperature in the furnace (right).

Figure 3.3: DNV's dedicated test facility including 500 kW high temperature kiln equipped with cooling infrastructure (right) and cooling floors (left) supporting the high temperature experiments

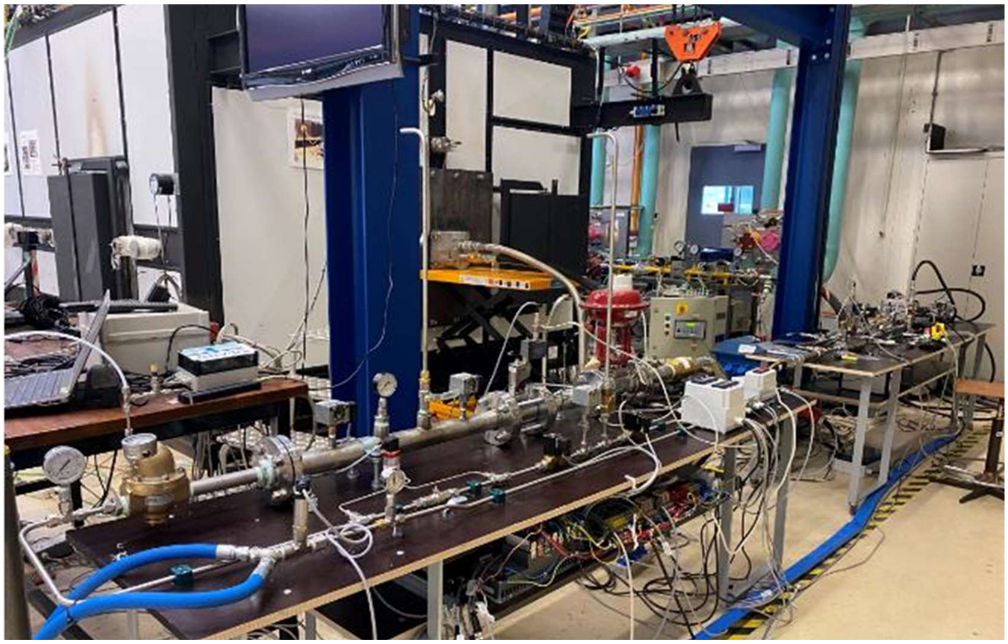


Figure 3.4: DNV's test facility including 500 kW high temperature kiln equipped with oxyfuel supply system(in front)

3.2 Fuel-adaptive burner control system

To enable a smooth switch from natural gas to hydrogen for industrial heating processes it is crucial to avoid shutting down the production process due to (temporary) unavailability of hydrogen. The project successfully tested a feed-forward fuel flexible burner systems that can utilize all fuel compositions of hydrogen and natural gas without manual adjustment, while maintaining optimal efficiency and a constant burner power. The optimized and integrated a fuel-adaptive control system in the burner management system ready to handle 100% hydrogen, 100% natural gas, and all mixtures of hydrogen and natural gas in between.

To control the fuel/air ratio and the thermal input, we used an in-house-developed fuel adaptive burner control system that was connected (as an add-on) to the Lamtec Etamatic BMS. The schematic overview of the fuel adaptive control system is illustrated in Figure 3.5. The gas composition measured in the fuel supply line upstream of the burner was used as input for the combustion algorithm (programmed in the PLC) that calculated the required fuel and air flow rates for a given gas composition to achieve the set fuel/air ratio and thermal input, respectively. The combustion air flow was controlled by both changing the fan speed by the PLC through a frequency controller and the air control (butterfly) valve position by the BMS by using a stepper motor. The fuel flow was controlled by the BMS by using a stepper motor as well.

The details of the combustion algorithms including an overview and performance of the gas quality sensors used in previous projects to measure the gas composition are described in the confidential report [6].

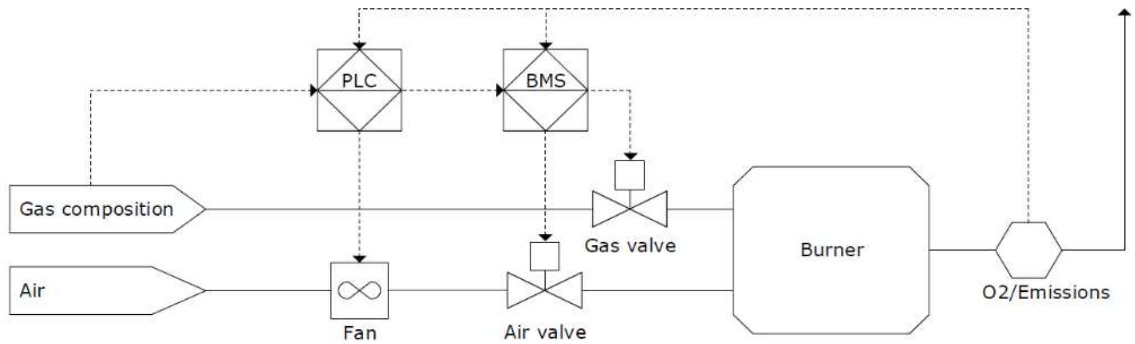


Figure 3.5: Schematic of the burner setup including fuel-adaptive control system

3.3 Burner safety system

Industrial combustion installations are usually operated without continuous supervision by an operator. Therefore, EN-746 and 12067 demand safeguarding functions and systems that meet at least the Safety Integrity Level (SIL)-3 reliability requirements. The flue gas sensor meets SIL-2 only and, therefore, the developed feed-forward gas-adaptive control system described above was considered to be too unreliable. Within this project this issue was solved by developing and implementing a new safety protocol that meets the requirements described in the (safety) standards which is described in detail in [1]. The core of the applied solution was that an additional safeguarding system was implemented. This additional safeguarding system was a feedback system that measured the CO equivalent (ppm) and oxygen percentage in the flue gas continuously by using a gas sensor. The burner would automatically be switched off when the CO or oxygen concentration measured was outside the set safety limit values. Both the (feed forward) gas quality signal and the (feedback) CO and O_2 signals were integrated in the burner management system. To achieve a reliable system (at SIL-3) the feedback flue gas sensor was checked continually by the BMS.

For hydrogen combustion, an addition challenge arises since hydrogen flames do not produce CO in the flue gases, but instable combustion can lead to substantial amounts of hydrogen in the flue gas. Hydrogen can form an explosive hydrogen/air mixture above 4% in air (Lower Explosion Limit or LEL). Since the CO sensor responds to (unburned) hydrogen in the flue gases, we recalibrated the CO sensor within the project [1] and used the CO sensor as a hydrogen safeguarding sensor. The setpoints used ensured that during operation the hydrogen concentration in the flue gases could not exceed 4000 ppm H_2, which is 10% of the LEL value and is considered to be the safe limit value for hydrogen.

4 COMBUSTION PERFORMANCE TEST RESULTS

This section describes the results of the burner test program. The details of the burner tests and analysis can be found in the confidential reports [1-6]. A general observation for all burner tests is that all the five burners tested, including the oxyfuel burner, show good combustion performance over the entire range of hydrogen/natural gas blends studied when applying fuel-adaptive control that keeps the thermal power and air factor constant.

However, depending upon the burner type and hydrogen percentage present in natural gas, the increase in NO_x emissions can be an issue. For low temperature processes such as steam and hot water production this NO_x increase is successfully reduced by applying external flue gas recirculation. For the industrial burners studied in the high temperature, reducing the NO_x emissions is still a challenge to be solved. Furthermore, hydrogen addition results in combustion closer to the burner which may impact the integrity (lifetime) of the refractory material near the burner, the burner block or, if applicable, the ceramic tube. This has not resulted in overheating of the burner head for the burners studied. Generally, the efficiency of the heat transfer to the cooling water does not change substantially. In several cases the heat transfer increased when switching from natural gas to hydrogen combustion, while keeping the burner power and lambda (air factor) constant.

To guarantee the safety, to monitor the emissions and the flame structure for hydrogen flames, detection technologies must be developed and tested. In this study, a NO_x emission measurement procedure was developed and tested for pure H_2/O_2 flames. These flames normally only produce water and oxygen, but due to air ingress nitrogen can enter the flue gas resulting in NO_x production. Furthermore, to visualize a hydrogen flame the company LAND developed a prototype infra-red camera which was successfully tested.

4.1 General performance of flame ignition and flame detection (UV)

For all burners tested, including the oxyfuel burner, the gas mixtures were smoothly ignited for both pure natural gas and hydrogen in the (cold) boiler and furnace. For the burners studied, a commercially available UV flame guarding (detection) system was installed and connected to the BMS. Generally, the UV detection system used showed no malfunctioning at all for the natural gas/hydrogen blends studied (0-100% H_2). However, the UV signal decreases substantially upon hydrogen addition, as can be seen in Figure 4.1. Here we remark that the change in UV signal upon hydrogen addition differs among the burners tested. Although no failure was observed during the measurements, we recommend, based on these results, to check the type and sensitivity of the flame detector installed before blending in hydrogen to natural gas to prevent that hydrogen addition results in a reduction of signal below the threshold value, and consequently a shutdown of the burner system.

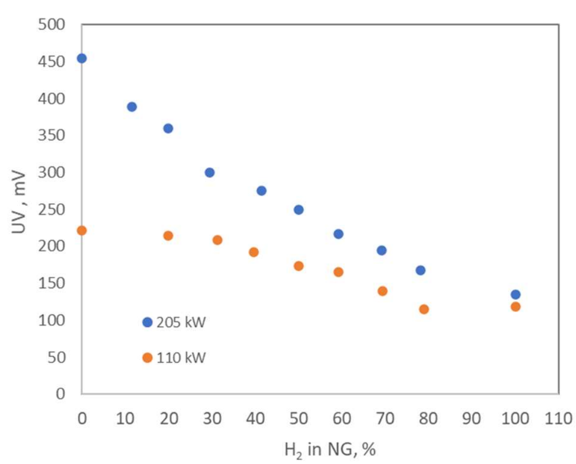


Figure 4.1: Effect of hydrogen addition (by volume%) on the flame signal of the UV sensor measured at 110 and 205 kW for burner no. 3.

4.2 Fuel adaptive control

The addition of hydrogen to natural gas will impact the chemical and physical properties of the gas mixture. For example, the density and the energy content of the mixture will change. Furthermore, the amount of oxygen needed for complete combustion changes upon hydrogen addition. As a result, hydrogen addition will result in a change in the thermal input of the burner (power) and the fuel-to-air ratio (λ).

When performing the measurements without the fuel adaptive control system (orange dots in Figure 4.2), as the volume of hydrogen increases to around 70%, the oxygen percentage in the flue gas increases, while the thermal input substantially decreases (from 125 kW-110 kW). When switching to pure hydrogen the oxygen percentage drops from 6.7 to 2.8% and the thermal input increases substantially up to 125 kW. These changes are expected based on the changes in air requirements and Wobbe index when hydrogen is added to natural gas. The experiments shown in Figure 4.2 are performed using burner no.2 in the furnace at a flue gas temperature of about 900 °C. At these conditions the observed increase in the oxygen concentration in the flue when 70 vol% hydrogen is present results in a decrease in the fuel thermal efficiency of about 11 percentage points. The observed changes in thermal input and decrease in thermal efficiency are unwanted for industrial heating processes.

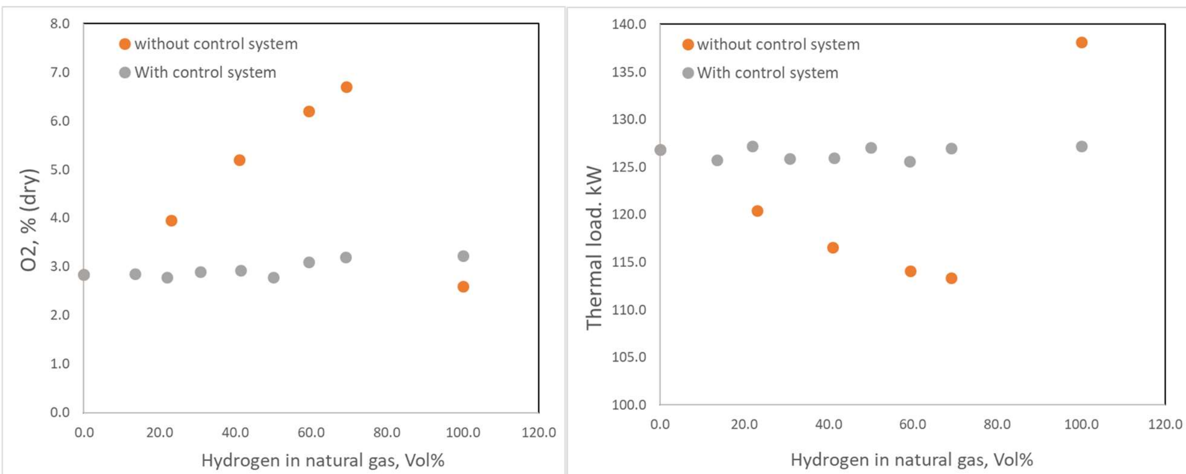


Figure 4.2. The effect of H_2 addition on residual oxygen percentage (left) and on the thermal input (right) measured at a furnace temperature of about 900 °C using burner no. 2 (Table 3.1)

When using the fuel adaptive control system, the air factor and the thermal input are kept constant by this control system. As a result, the air factor (residual oxygen percentage) and the thermal load presented in Figure 4.2 are kept constant upon hydrogen addition to natural gas. From this, we conclude that the fuel adaptive control system allows to maintain power and efficiency over the entire studied range of hydrogen/natural gas mixtures (0-100 vol% H_2).

4.3 Changes in flame structure

When hydrogen is added to natural gas, the physical and chemical properties change, and this can affect the flame structure. For example, Figure 4.3 shows that the combustion velocity increases substantially upon hydrogen addition. Furthermore, as shown in Table 4.1, the explosion limits are much wider for hydrogen. Besides that, the chemical properties, the physical transport phenomena, molecular diffusion, density, and fuel velocity will change. For example, when changing to hydrogen combustion, while maintaining the burner power, the fuel velocity should be increased to a factor of about three to compensate for the decrease in calorific value when switching from natural gas to hydrogen. These changes can have an impact on the flame structure and heat distribution within the flame. More details of the theoretical determined changes in the physical and chemical properties of the gas upon hydrogen blending can be found in [1-7].

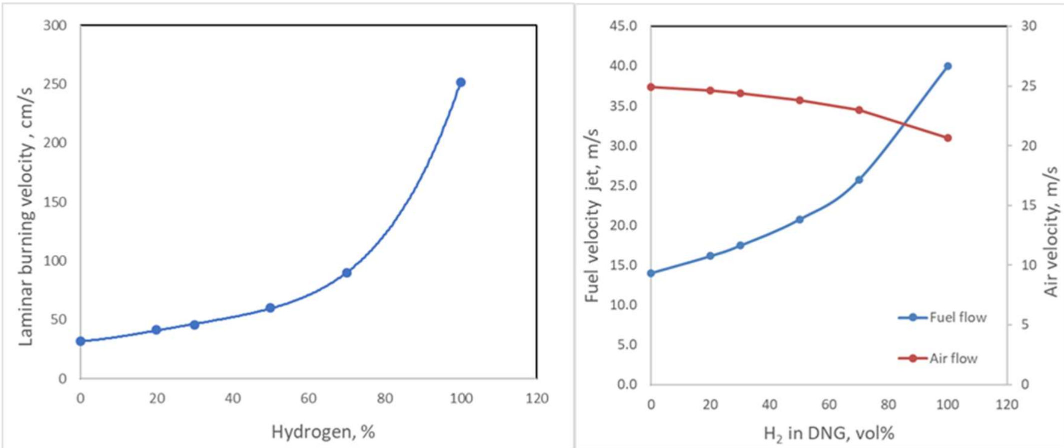


Figure 4.3: Calculated Laminar burning velocities at λ=1 (left) and the changes in fuel velocity to maintain constant power 200 kW at λ=1.1 (right).

Table 4.1: Physical parameters of Dutch natural gas and hydrogen

	Dutch natural gas [1]	Hydrogen
LEL, %	5.8	4.0
UEL, %	16.7	75.3
Minimum ignition energy (stoichiometric mixture)	0.274	0.017
AIT, °C	630	520
Wobbe index, MJ/m^3 (25, 0)	43.75	48.35
Net calorific value, MJ/m^{3}n	30.86	10.79
Gross calorific value , MJ/m^{3}n	34.24	12.75
Density, kg/m^{3}n	0.79	0.09
Ionization current in flames (flame guarding system)	Sufficient ionization to detect if there is a flame present	Not sufficient ionization to detect if there is a flame present

To study the impact of hydrogen on flame structure, flame images with a CCD camera and the new prototype IR camera were taken. The effect of hydrogen addition strongly depends upon the burner type used. However, generally no large changes in the visual flame shape were observed upon hydrogen addition [1-5], when keeping the thermal input (power) and the air factor constant. As an example, Figure 4.4 shows the flame images from burner no. 4 (Table 3.1) taken with a CCD camera. The images show a change in colour from a yellow (sooting) flame up to 50 vol% hydrogen. At 70 vol% hydrogen the colour becomes blue because of the emission from the carbon containing molecules which are not visible at 0-50 vol% hydrogen flames (the bright emission from the soot particles is dominating in these flames). At 100% hydrogen the colour of the flame becomes orange. Although the flames seem tighter at 50 and 70 vol% hydrogen, no large changes in the visible flame length were observed upon hydrogen addition.

[1] Typical gas composition of Dutch natural gas: CH_4=82.9%, C_2H_6=3.2%, C_3H_8=0.4%, C_4H_{10}=0.1%, N_2=9.6%, CO_2=3.9%

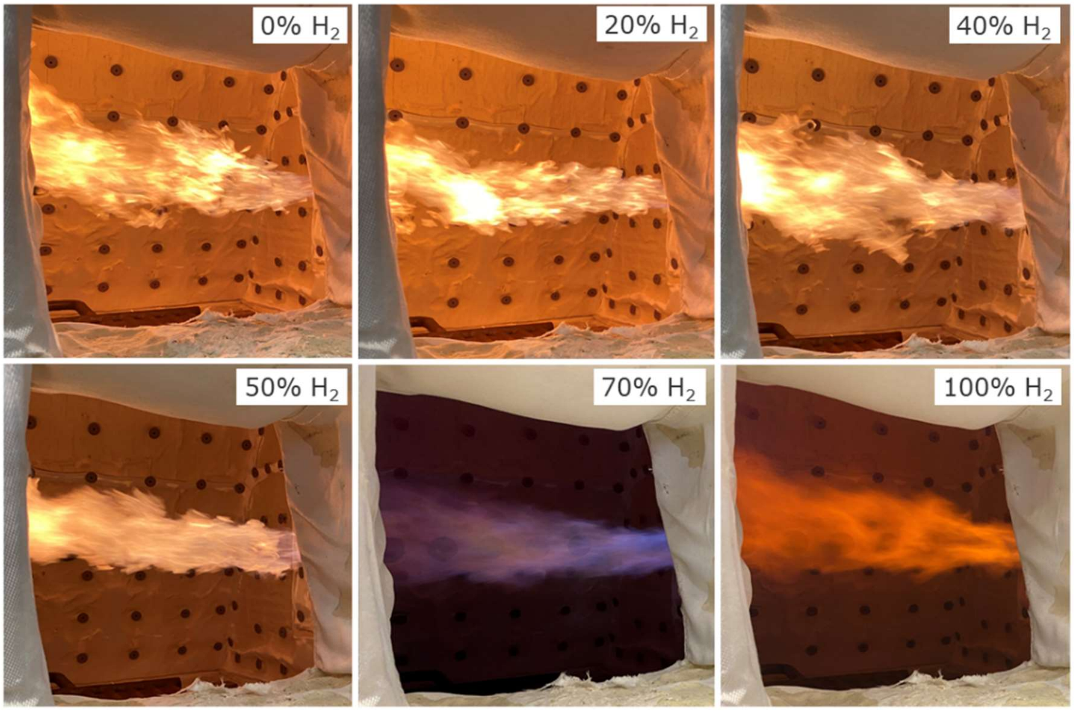


Figure 4.4: Flame images using a CCD camera (120-degree angle), at 210 kW and λ=1.1.

The IR flame images presented in Figure 4.5 provide insight in the changes in heat distribution within the flame. Figure 4.5 shows that for pure natural gas the hot flame zone is positioned ‘far’ downstream of the burner. This allows entrainment of flue gases into the cold (unburned) jet. However, when hydrogen is blended into natural gas, the hot flame zone (white/red coloured areas) moves closer to the burner head as a result of more combustion that takes place closer to the burner. The combustion upon hydrogen addition is enhanced by faster mixing of fuel and air, widening of the flammability limits and the increase in the burning velocity.

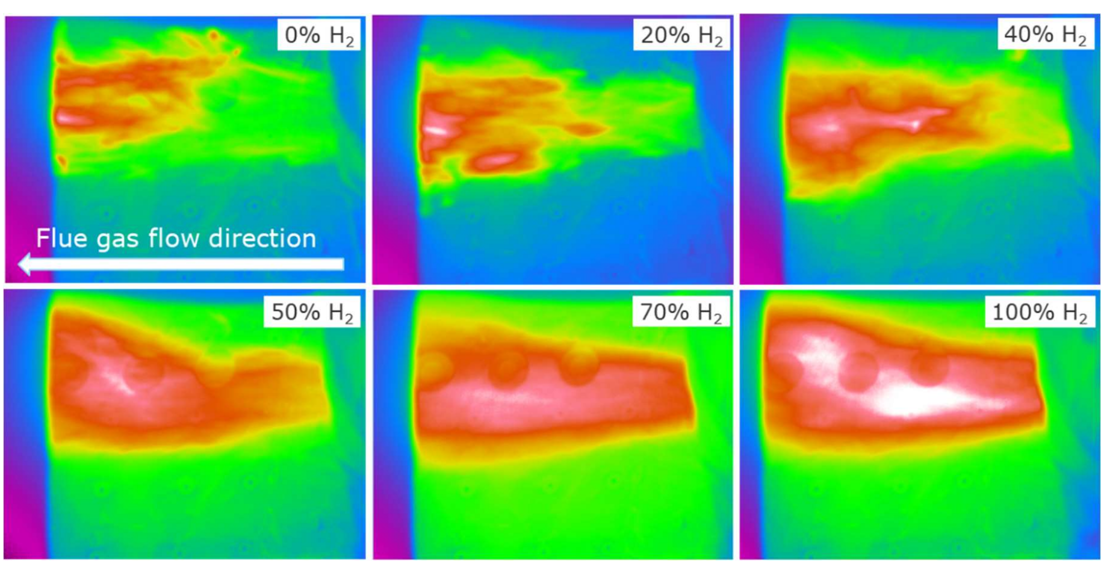


Figure 4.5: Flame images using an IR Land camera, at 210 kW and λ=1.1.

The shift of the hot flame zone closer to the burner was observed for the majority of the burners studied. This is also confirmed by the CFD analysis performed in this study [7] and by the in-situ temperature measurements performed with the in-situ CelSian IR laser detection system. The in-situ temperature was measured in such a way that the laser beam propagates partially through the flame (including the flame front). The results show that the temperature increases substantially upon hydrogen addition – from 970 °C for pure methane to 1150 °C for pure hydrogen. The steep increase in temperature suggests that the hot zone of the flame moves closer to the burner block as observed as well in the CFD analysis and the IR flame images (see for example Figure 4.5). Inspection of the burner block refractory material did not show any deterioration, but it is recommended to further analyse the long-term impact on the refractory material when using hydrogen as a fuel. Although more combustion takes place near the burner head no overheating of the burner itself was observed upon hydrogen addition. We attribute this to the increased cooling of the fuel nozzle (increased fuel velocity and increase thermal conductivity) upon hydrogen blending. The details of these measurements are described in [5].

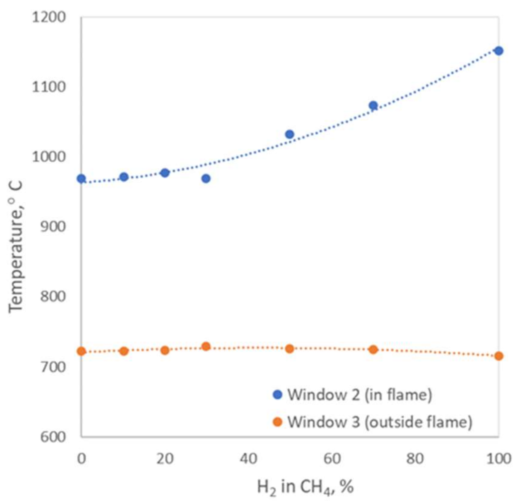


Figure 4.6: in-situ temperature measurements in window 2 (including flame) and window 3 (outside flame) for burner no. 5

To illustrate that different burner types give different flame shapes, we present the hydrogen flame images when using a natural gas oxyfuel burner (Figure 4.7, left), as is typically used for glass melting processes, and a hydrogen flame (Figure 4.7, right) produced by using a high velocity natural gas burner, as is often used in the ceramic industry. The images clearly show different flame shapes when using the same fuel. The effects of hydrogen addition on the flame shapes of all burners studied are described in detail in reports [1-5].

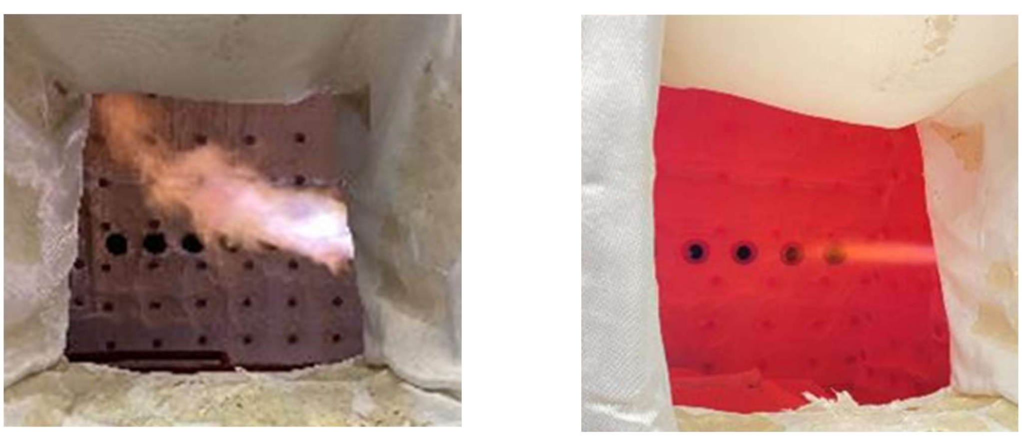


Figure 4.7: H_2/O_2 flame using a natural gas oxyfuel burner (left) and a H_2/air flame using a high velocity burner (right)

4.4 Effect of hydrogen blending on NO_x emissions

Blending hydrogen into natural gas can have an impact on NO_x emissions. The impact will depend on the burner design, burner settings (load and air factor), and furnace/boiler conditions (temperature), To study this impact, NO_x emission measurements were performed for all burners studied, using air or oxygen as an oxidizer. Generally, as shown in Figure 4.8 for the burners studied, a different behaviour was observed with regard to NO_x emissions upon hydrogen addition. Here we note that we did not perform quantitative comparisons among the burners studied since each experiment was performed at different conditions such as furnace temperature, air ratio and burner load. The selected test conditions were chosen to reflect the process where the burner is typically used for. However, we observed qualitatively interesting differences. For example, for burner types no. 1, 2 and 4 an (exponential) increase in NO_x was observed, primarily at high hydrogen content. In contrast, burner no. 3 initially showed a substantial increase in NO_x emissions upon hydrogen addition followed by a decrease above 80 vol% hydrogen. The difference in the behaviour is attributed to the change in the degree and rate of mixing, rate of diffusion of hydrogen, combustion speed, flame temperature and flammability limits causing combustion to take place closer to the burner when hydrogen is added, as is illustrated in Figure 4.5. For burners 1, 2, and 4 the degree of mixing near the burner was rapid, resulting in faster combustion and local higher temperature areas, and hence higher NO_x formation near the burner upon hydrogen addition. For the high-speed burner (no. 3) the mixing of the flue gas, combustion air and the fuel jet differed from the other burners, resulting in a different NO_x emissions behaviour. For this burner the reduction in residence time, the higher rate of diffusion of hydrogen and the change in adiabatic flame temperature played an important role in the observed NO_x behaviour. A more detailed NO_x formation analysis is provided in [1-5, 7].

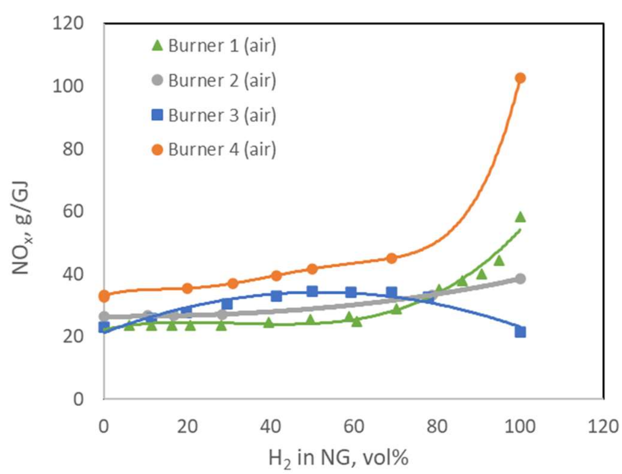


Figure 4.8: NO_x emissions measured for the different burners presented in Table 3.1

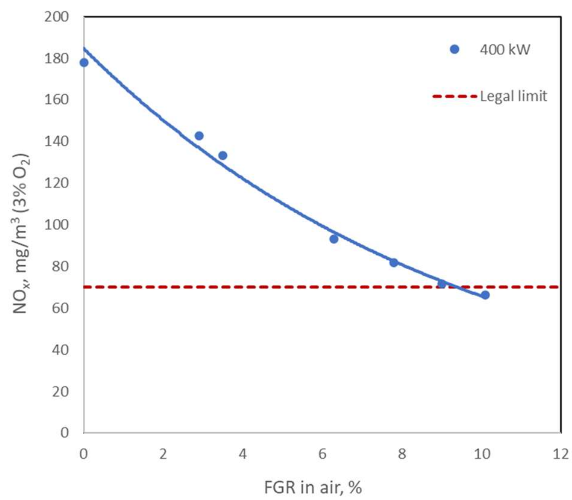
In oxyfuel combustion, ideally zero NO_x is expected since no nitrogen is present in the fuel. During the tests in the furnace using the oxyfuel burner no. 5 (see Table 2.1), NO_x emissions were measured due to air ingress in the furnace. Although not presented, hydrogen addition to natural gas resulted in a 15% increase in the NO_x formation when 20 vol% hydrogen was present in natural gas. For percentages higher than 20 vol% hydrogen in methane the NO_x emissions were found to decrease linearly. The results obtained show a reduction in NO_x emissions of about 20%, when switching from methane to pure hydrogen operation.

From the results obtained in this study we conclude that hydrogen addition to natural gas generally results in an increase in NO_x formation, but that quantitative and qualitative NO_x behaviour strongly depends upon the burner type and process conditions used.

4.5 NO_x mitigation strategies

To successfully introduce hydrogen as a fuel for heating processes, NO_x emissions should not increase compared to the NO_x values when natural gas is used as a fuel. To decrease NO_x emissions of the forced draught boiler burner no 1 (see Table 2.1) upon hydrogen addition, external flue gas recirculation was applied. When applying flue gas recirculation, a part of the flue gases was returned to the combustion air inlet. The dilution of the air with (inert) flue gases reduced the adiabatic flame temperature, and consequently reduced the (thermal) NO_x formation. The amount of flue gas recirculation applied was controlled by a control valve which was connected to the Burner Management System. The aim was to reduce the emissions below the legal limits while maintaining stable and efficient combustion. Given that a hydrogen flame has the highest NO_x emissions, we studied experimentally how much flue gas recirculation we would have to apply to reduce NO_x emissions below the (Dutch) legal limits of 70 mg/m^3 (at 3% O_2 in the flue gases). The experiments were performed at a thermal input of 400 kW and at an air factor of λ=1.2 (~4% O_2). As can be seen in Figure 4.9, about 9 mole% flue gases in the combustion air was needed to bring NO_x emissions below the legal NO_x limits.

Based on the insights and technology developed in this study, the company Nedmag (partner in the consortium) is currently making the preparations for a large-scale demonstration project, converting a 2 MW natural gas fired oil heating furnace to a hydrogen flexible (0-100% H_2 in natural gas) oil heating furnace. The experiments at Nedmag are planned to take place in Q4 2022.



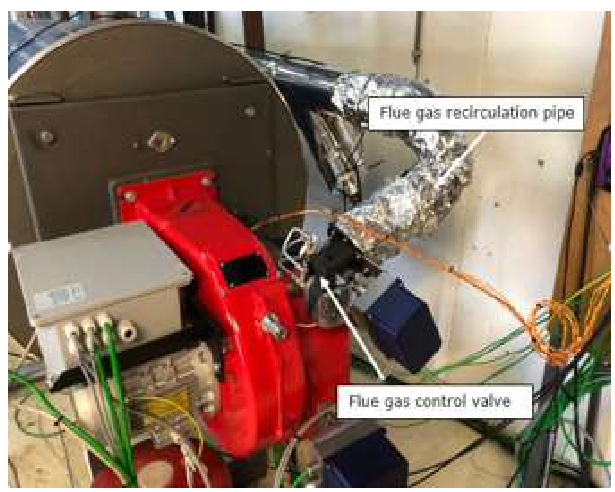


Figure 4.9: Effect of applying flue gas recirculation in the combustion air on NOx emissions at λ=1.2 and a thermal input of 400 kW (left) and flue gas recirculation applied on the burner/boiler system (right)

Applying external flue gas recirculation is relatively easy for low temperature heating processes, such as hot water and steam boiler systems, since the flue gas temperatures are below 500-600 °C. For high temperature heating processes, applying external flue gas recirculation is more complex and expensive, since the flue gas temperature is high and thus cooling of the flue gases is required. Tests performed in this study, showed that diluting hydrogen with small amounts of nitrogen is an effective method to reduce NO_x emissions for the majority of the burners tested in the high temperature furnace. However, it is strongly recommended to optimize the design of the burner to lower NO_x emissions. The necessary changes in the design depend strongly upon the burner type used. In general, the new design should enable (slower) mixing (fuel/air) at a later stage, improving flue gas entrainment and/or lowering the residence time. This can be done by, for example, changing the velocities of the fuel and air jets, creating more internal flue gas recirculation, or changing the position of the fuel lance.

4.6 Novel H_2/O_2 combustion system for low temperature heating processes

The aim of this developed combustion system is to generate heat by combustion of H_2/O_2 (oxyfuel) mixtures in (existing) industrial boilers. In this operating mode, zero NO_x and CO_2 emissions can be achieved. In order to implement this technique in conventional boilers, large amounts of flue gas recirculation (mainly H_2O) need to be applied. This reduces the flame temperatures to a comparable level to conventional natural gas and/or hydrogen combustion with ambient air. In additional, this minimizes the impact of a changing amount of flue gasses passing through the convective heat transfer areas of the boiler by the omission of nitrogen present in the ambient air.

The concept of changing from a conventional operating mode to full oxyfuel mixture operation and vice versa was demonstrated by the combustion trials conducted on the hot water boiler in the laboratory of DNV. The test installation used for these tests consists of a burner/boiler configuration, fed by natural gas and/or hydrogen gas as a fuel (both 100% natural gas operation and 100% hydrogen operation are possible, including any binary blend). For oxidation, fresh air and pure oxygen were available which could be diluted further with pure nitrogen and/or flue gas recirculation. See Figure 4.10 for a brief overview of the system and the actual test environment. Figure 4.11 shows the constructed test installation.

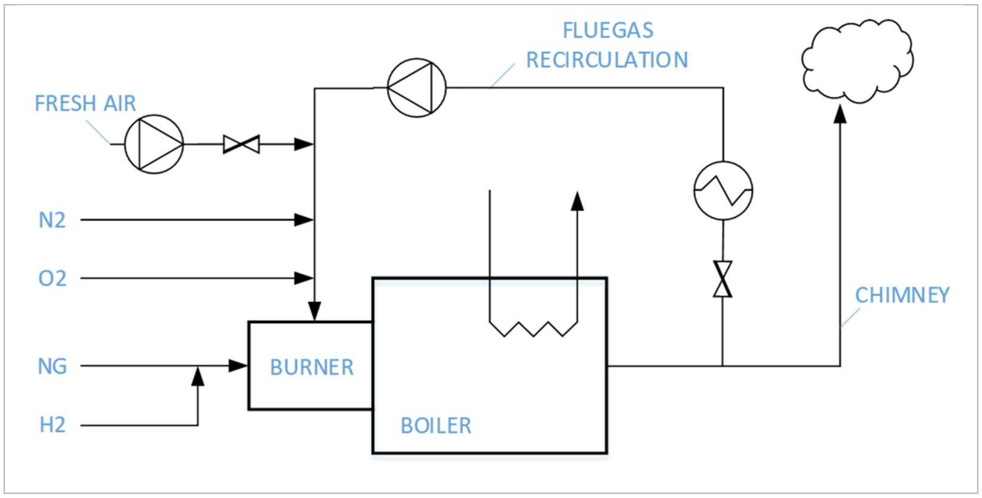


Figure 4.10: System configuration diagram of oxyfuel test installation

Safeguarding the installation was done by means of implementing various alarms, trip conditions and sequences into a PLC cabinet (burner management system / BMS). Besides the frequently used safeguards following from normative requirements typical in place for burners in industrial installations, additional provisions were implemented. These included, for example, oxygen safety and preventing flue gas condensation. The latter is necessary due to the flue consisting of mainly water vapour when operating on oxyfuel conditions. For flame detection, commercially available IR+UV type flame scanners were suitable during all possible combustion scenarios, ranging from conventional fresh air with natural gas to oxyfuel conditions.

The installation was typically started on natural gas whilst firing with only fresh air. From this operating point either the flue gas recirculation or starting hydrogen was possible. The effect on NO_x emissions of blending an increasing amount of hydrogen with natural gas is shown in Figure 4.12. In addition, the NO_x reduction of adding flue gas recirculation is shown in Figure 4.12.

Figure 4.11: Overview of constructed oxyfuel test installation

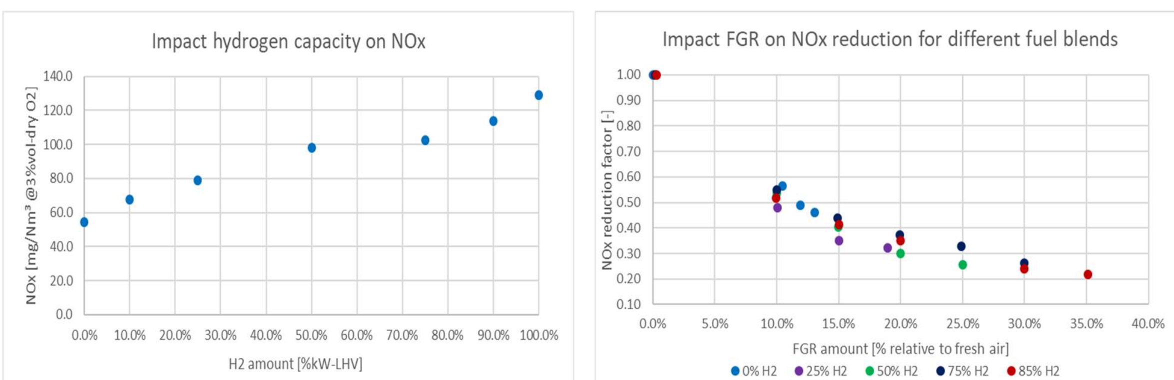


Figure 4.12: Overview of the impact of increased hydrogen blending on NO_x emissions and the effect of NO_x reduction by increasing the flue gas recirculation flowrate for different blends

Departing from the operating mode on pure hydrogen fuel in combination with a moderate amount of flue gas recirculation, the oxygen supply could be started in order to traverse towards oxyfuel operation. An initial change-over strategy was to increase the amount of oxygen and decrease the amount of fresh air after. The flue gas recirculation was increased as such that the total flow to the boiler was kept relatively constant in balance with the total flow and calculated flame temperature. For the test installation this strategy was found to be sufficiently suitable, however for steam boilers a slightly more optimized strategy might be preferable in order to minimize impact of the boiler water/steam balance.

During oxyfuel operation of the installation the NO_x emissions were observed to slowly decline towards near-zero ppm. A significant amount of time was required for the majority of nitrogen molecules to exit the system, due to the relatively large amount of flue gases recirculated back to the burner. Safeguarding of the burner flame was proven to be suitable by readily available dual cell flame scanners. It was observed that the UV signal decreased rapidly when more hydrogen/oxygen/water vapour were present in the flame zone. However, the IR signal did increase, providing sufficiently good signals for proper flame detection. Additional safeguarding provisions such as oxygen high safeguarding by in-situ O_2 measurements and prevention/detection of water vapor condensation were tested successfully to be effective.

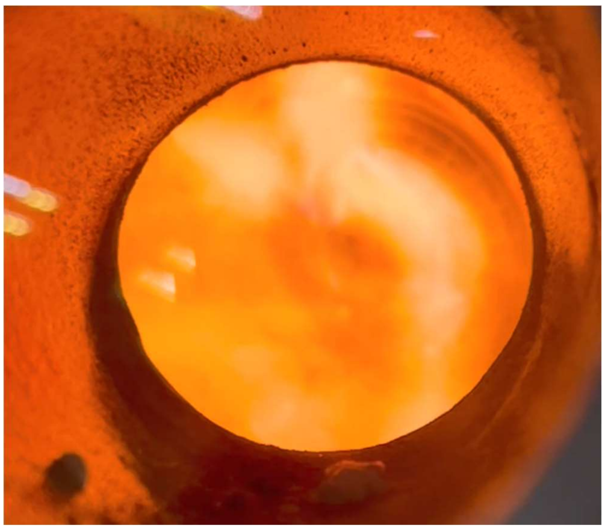


Figure 4.13: Flame image taken during oxyfuel operation mode

An outcome of the experiments conducted, was that the proof-of-principle of the novel hydrogen combustion burner system was demonstrated successfully. Transition from conventional operation with fresh air and hydrogen to oxyfuel conditions and vice-versa was repeatedly conducted. The system was further optimized prior to and during the tests in order to prevent occurrence of flue gas condensation as much as possible (within limitations of the boiler system used), in combination with emphasizes on the oxygen safety aspects.

An outcome of the experiments conducted, was that the proof-of-principle of the novel hydrogen combustion burner system was demonstrated successfully. Transition from conventional operation with fresh air and hydrogen to oxyfuel conditions and vice-versa was repeatedly conducted. The system was further optimized prior to and during the tests in order to prevent occurrence of flue gas condensation as much as possible (within limitations of the boiler system used), in combination with emphasizes on the oxygen safety aspects.

4.7 Heat transfer

Replacing (a part) of the natural gas with hydrogen causes changes in the flame temperature, gas composition and flow distribution. These changes can have consequences for the heat transfer to the products to be heated and the heat distribution within the furnace. However, at present the impact of hydrogen blending on the heat transfer is unknown. To study the changes in heat distribution, temperature measurements were carried out during the tests using fixed thermocouples installed in the crown and furnace's walls. Furthermore, the changes in the heat transfer to the cooling floors were measured upon hydrogen addition.

The results of this study show that the influence of hydrogen addition to natural gas on the heat transfer depends upon the type of burner system used. However, generally we observe that hydrogen addition does not have a major impact on the heat distribution, and that the heat transfer to the cooling floor increases. As an illustration, in Figure 4.14, the temperatures measured in the crown (left) and along the walls of the furnace (right) are given for burner no. 5. The measurements presented in Figure 4.14 show a slight reduction in temperature with the hydrogen concentration in the fuel blend. This is in agreement with the higher heat absorbed in the cooling floors at the same conditions showed in Figure 4.14. Switching to hydrogen improves the heat transfer to this zone of the furnace, adding the strong contribution of the convective heat transfer, due to the velocity changes upon hydrogen concentration. For some of the burners where air is used as oxidizer, the radiative heat transfer ($Q=\sigma\varepsilon T^4$) increases upon hydrogen addition as a result of the increase in the size and temperature of the hot flame zone. These results can be found in [1-4].

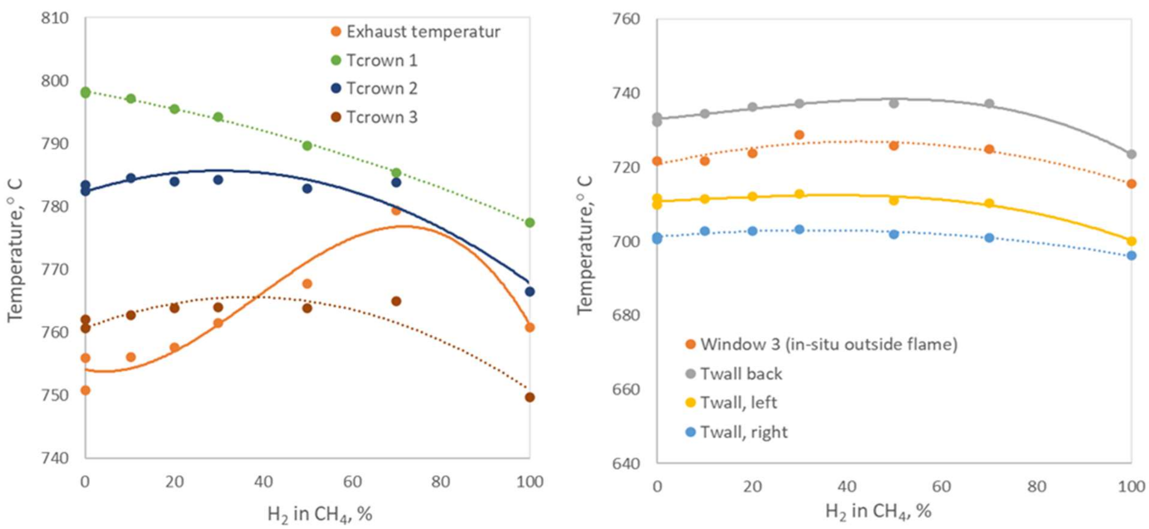


Figure 4.14 Left: in-situ temperature measurements in window 2 (including flame) and window 3 (outside flame). Right: thermocouple measurements at different positions near the walls.

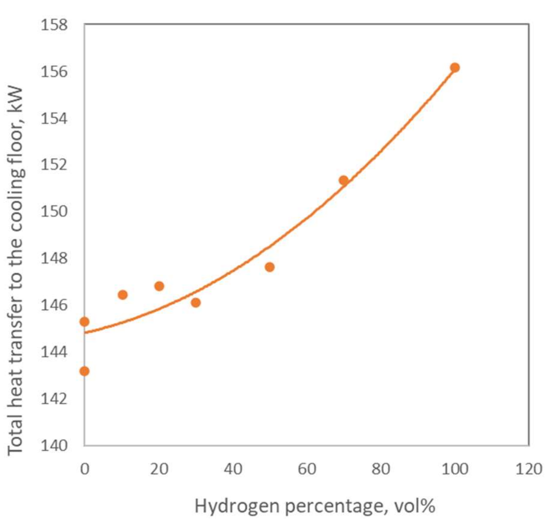


Figure 4.15: Heat transfer to the cooling floors with hydrogen concentration in the fuel blend

5 MEASUREMENT AND DETECTION TECHNIQUES

Measurement techniques used in the industry are mainly designed for monitoring natural gas combustion. In this study it is demonstrated that commercially available UV flame detection systems can be used, but – as illustrated in Figure 5.1 – the flame signal decreases upon hydrogen addition. To monitor the flame structure a new prototype IR camera developed by the company LAND was tested. The IR camera uses the H_2O emission lines to visualize the flame structure, since both hydrogen and natural gas produce water upon combustion. The tests show that the IR camera enables detection of the heat distribution of all studied hydrogen, hydrogen/methane, and pure methane flames. However, it is recommended to further optimize the camera to improve the visualisation of the flame structure. The CelSian IR laser system, used to monitor the temperature, CO, H_2O, and CO concentration in-situ in glass (or other high temperature furnaces), was successfully recalibrated for hydrogen blends up to 100% hydrogen. The in-situ measurements show generally good results for all studied fuel blends. However, for pure hydrogen the H_2O concentration in the flame front showed values (130%) that were too high. Therefore, recalibration for H_2O is recommended.

As safety system the O_2, CO and H_2 is detected successfully when using the studied H_2/natural gas blends (0-100% H_2) in the wet exhaust gases using a zirconium dioxide oxygen sensor [2-5]. Furthermore, a method to reliably measure NO_x emissions in dry flue gases was successfully developed and tested for pure hydrogen mixtures [5], which is challenging since the only combustion products (in the flue gases) are water, oxygen and NO_x (from air ingress). However, it is recommended to develop techniques for pure hydrogen that allows performing reliable NO_x measurements in flue gases with very high water concentrations [5].

Figure 5.1 Measurement techniques used during burner test program: radiation flux sensor (left) and IR camera (right)

6 HEAT TRANSFER - CFD ANALYSES

As indicated before, various combustion characteristics of hydrogen deviate from the combustion characteristics from natural gas. This requires fundamental understanding of the impact of these deviations on combustion and heat transfer processes in order to (re-)design industrial glass furnaces that adopt green fuels. Mathematical simulations have been performed to cross-validate the results of the pilot combustion tests with combustion models of (blends of) hydrogen (and natural gas). Validated simulation models enable the prediction of the behaviour of industrial glass furnaces that are fired with (blends of) hydrogen in combination with air or oxygen. Thereby, optimized process settings and/or furnace designs modifications can be determined to safeguard glass quality, furnace lifetime, energy efficiency, and emissions when converting glass furnaces to (partly) hydrogen combustion.

In the first stage of the project, the pilot combustion facility was implemented in CelSian's glass furnace simulation model GTM-X. This enabled the simulation of the heat and mass transfer processes during combustion of (blends of) the gaseous fuels natural gas and hydrogen with air and oxygen. The combustion process was simulated for two different types of burners. The first burner was an air-fuel burner from burner no.2 (Table 2.1) whereas the second burner was an oxyfuel burner from burner no. 5 (see Table 2.1). For each burner, natural gas was replaced by mixtures of natural gas and hydrogen and by pure hydrogen. The results of the numerical simulations were compared against measurements performed by DNV.

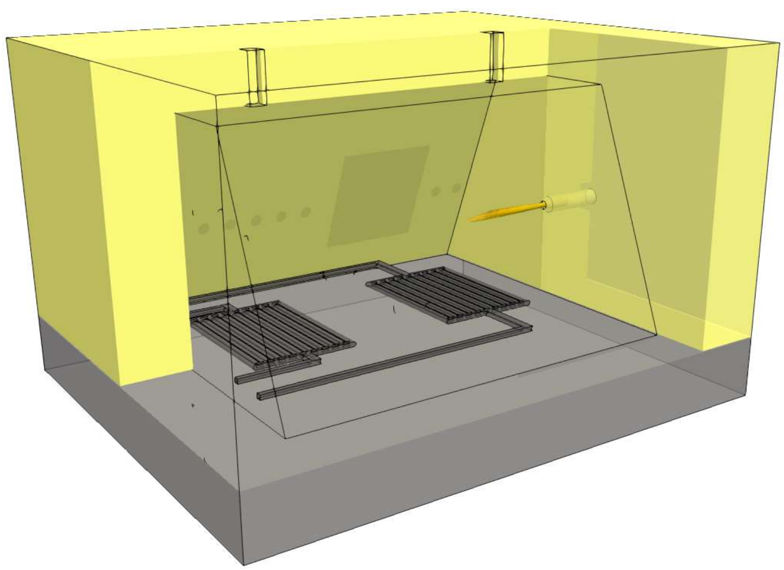


Figure 6.1: Geometry of the pilot combustion furnace that is simulated with the CelSian CFD code GMT-X

Comparison of combustion simulation results with the pilot combustion facility

For both burners, the simulation results (flame shape, temperatures and NO_x values) are in good agreement with the measured values. It shows that glass furnace simulation is well suited to describe combustion of hydrogen or blends of hydrogen and natural gas with air and oxygen in glass furnaces. Like for natural gas combustion, glass furnace simulation is a predictive tool to describe the behaviour of industrial glass furnaces in which natural gas is (partly) replaced with hydrogen. In more detail, both the simulations and the experimental testing show that the direct replacement of natural gas by hydrogen, using the conventional natural gas burners mentioned above, is feasible. The main challenge in terms of furnace operation probably corresponds to the possibility of overheating the burner block and pipe. This is caused by the faster combustion of hydrogen compared to natural gas moving the hottest part of the flame more towards the tip of the burner block.

The measured NO_x emissions follow different trends for air and oxygen combustion upon (partly) replacing natural gas with hydrogen. For air combustion (applying burner no. 2), the amount of NO_x increases with hydrogen combustion compared to natural gas combustion. For oxygen combustion (applying the burner no. 5), the amount of NO_x, in general, decreases when the content of hydrogen in the fuel composition increases. The simulated NO_x emissions follow the same trends as shown by the measurements. Therefore, it can be concluded that the model describing the formation of NO_x provides an accurate prediction of the actual NO_x emissions measured in the pilot combustion facility. The agreement of the simulated NO_x values is best for the case in which air preheating is applied. This indicates that for industrial applications with combustion air preheating, the NO_x emission predictions are accurate and enable the evaluation of the impact of design and process changes for industrial furnaces regarding NO_x concentrations in case (blends of natural gas and) hydrogen is combusted.

Simulating the impact of combustion air preheating on NO_x emissions

In the second stage of the project, a representative end port fired container glass furnace was modelled. The main goal of this part of the study was to assess the effect of air preheating temperature on NO_x emissions for an industrial container glass furnace applying common natural gas pipe-in-pipe burners for pure hydrogen combustion. Next to the impact on NO_x emissions, this also evaluated the effect of combustion preheating temperature on concentration of combustion species and general combustion behaviour (flow patterns, temperature levels and combustion process efficiency). Because of higher combustion air preheating temperature, the fuel consumption of the furnace reduced (to maintain a constant glass melt temperature) and the residence time of the flue gas components in the hot flue gases increased. Both lower fuel flow rate and longer residence time of the hot flames and flue gases in the combustion space, resulted in a lower energy consumption values in case of increased combustion air preheating temperature.

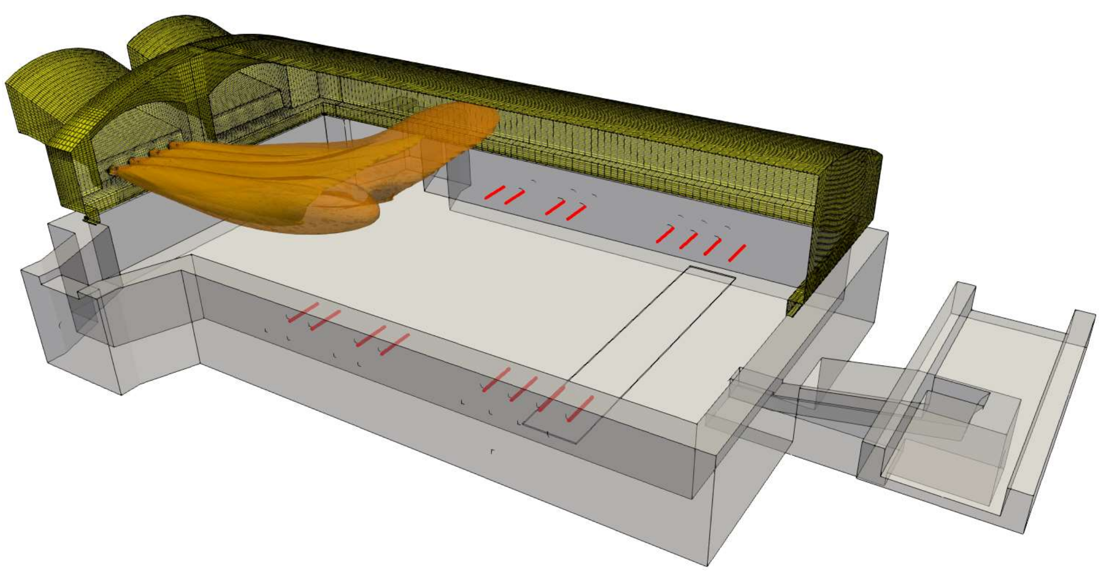


Figure 6.2: Schematic view of the regenerative end-port container glass furnace for which the impact of combustion air preheating temperature on NO_x emissions in case of hydrogen combusted is studied

At the same time, in case of a higher combustion air preheating temperature, NO_x emissions slightly increased (1.8%). This increase in NO_x emission values is likely due to slightly higher flame temperatures. In addition, a longer residence time of flue gas components (resulting from the lower flue gas volume) at the high temperature (where NO_x is formed), also contributed to slightly higher NO_x concentrations. In the study, for the case of increased combustion air preheating temperature, no optimization was done to find improved burner settings that would result in lower NO_x emissions. The lower fuel rate of hydrogen in case of the high combustion air preheat temperature provided more space to create a slightly longer flame and thereby avoiding high flame temperatures that are critical from the perspective of NO_x emissions.

Summarizing the simulation studies presented in this section, we can conclude the following:

- Pure hydrogen and blends of hydrogen and natural gas being combusted with air or oxygen are feasible fuels to reduce the CO_2 footprint of glass melting furnaces.
- Simulation of the combustion of these fuels in the DNV pilot combustion facility using existing burners show a good agreement with the measured and observed behaviour of the flames in the DNV pilot facility and also with the measured NO_x concentrations and heat fluxes.
- Glass furnace simulation is a predictive tool to describe the industrial behaviour of glass furnaces in which natural gas is (fully or partly) replaced with hydrogen.
- Because of the higher combustion rate of hydrogen, the hottest part of the flame obtained by combustion hydrogen might move back towards the tip of the burner (block); additional measures to prevent overheating of the burner tip and burner block might be required.
- Regarding NO_x emissions with hydrogen-oxygen combustion, it is shown (by both simulations and pilot testing) that NO_x emissions decrease as the fraction of hydrogen in the fuel increases; for hydrogen-air combustion, the NO_x emissions increase as the fraction of hydrogen in the fuel increases; it is noted that this behaviour should not be generalized to all oxyfuel and air-fuel burners since the combustion behaviour is dependent on the burner and furnace design.
- An increase in NO_x emissions with hydrogen combustion (compared to natural gas combustion) and/or with an increased combustion air preheating temperature, might be compensated for by optimization of burner settings and/or mixing of fuel and oxidant. This topic was not investigated because it is not the aim of this study.

7 RECOMMENDATIONS

The results of this study reveal that the performance of the commercial burners tested for different hydrogen blends show promising results which put the possibility of applied hydrogen combustion into the reach of the industry within the coming decade.

Generally, for all five natural gas burners tested, including the oxyfuel burner, the project observed good and safe combustion performance over the entire range of hydrogen/natural gas blends studied, when applying a fuel adaptive control system that keeps the thermal power and air factor constant. However, significant differences in combustion behaviour were observed for individual burners. Further study and performance testing is needed to understand the details for a specific situation.

It is recommended to further optimise and develop (retrofit) burner technology to increase and improve the heat transfer and heat distribution and minimise **NO_x formation**. For example, the experiments showed that the hot zone of the flame shifts closer to the burner upon hydrogen addition which can impact the lifetime of the burner block material and the burner itself. In addition, for the majority of the burners studied NO_x emissions increase substantially with increasing hydrogen content in natural gas. Optimizing the burner configuration by, for example, delaying the combustion and improving internal flue gas recirculation will reduce NOx emissions and move the hot zone further away from the burner block. NOx emission measurements for oxyfuel-hydrogen combustion are complex, and it is recommended to develop in-situ NOx measurements for these processes.

The changes in flue gas composition and flame temperature caused by hydrogen addition may impact the **refractory material** of the furnace and consequently may shorten its lifetime. It is therefore recommended to study the effect of hydrogen blending on the refractory lifetime.

Furthermore, it is strongly recommended to initiate and undertake **industrial field pilots** to learn under realistic conditions and develop rules and standards for hydrogen combustion systems and hydrogen supply infrastructure. In this field pilots also important experiences on safety procedures and permitting can be achieved

8 ACKNOWLEDGEMENT & PARTNERS

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Project partners:

9 REFERENCES

1. S. Gersen, B. Slim, R. Zeijlmaker, Phase 1: Forced draught burner tests, ‘Hydrogen as a fuel for heating processes’ (2021) (only available for project partners)
2. S. Gersen, B. Slim, R. Zeijlmaker, Phase 2: Measurement results of the BIC burner tests, ‘Hydrogen as a fuel for heating processes’ (2021) (only available for project partners)
3. S. Gersen, B. Slim, R. Zeijlmaker Phase 3: High velocity burner tests using CH4/H2 blends, ‘Hydrogen as a fuel for heating processes’ (2022) (only available for project partners)
4. S. Gersen, B. Slim, R. Zeijlmaker, Phase 4: VitroGLO-RP burner tests using natural gas/H2 blends, ‘Hydrogen as a fuel for heating processes’ (2022) (only available for project partners)
5. S. Gersen, B. Slim, R. Zeijlmaker, Phase 5: Oxy-fuel burner tests using CH4/H2 blends, ‘Hydrogen as a fuel for heating processes’ (2022) (only available for project partners)
6. S. Gersen, B. Slim. Fuel adaptive control algorithm and gas quality sensor inventory and tests, ‘Hydrogen as a fuel for heating processes’ (2021) (only available for project partners)
7. R. Carneiro, L. Thielen, L. de Cock, J. Dennen, O. Verheijen, DNV – Test furnace modelling study ‘Conversion from natural gas to hydrogen combustion in diffusion burners’, REP-632.002 (2022) (only available for project partners)

10 PUBLICATIONS, KNOWLEDGE DISSEMINATION AND PRESENTATIONS

- Sustainable Industrial Manufacturing Europe 2022 ‘Cutting Industrial heat emission for clean growth (28-06-2022)
- Sander Gersen, Impact of sustainable gases on end-use equipment performance, GlassTrend seminar ‘Application of sustainable technologies in energy-intensive industries’, 24 March 2021
- Sander Gersen, Hydrogen as a fuel for industrial heating processes, GlassTrend webinar, 18 May 2021
- Oscar Verheijen and Sander Gersen, Hydrogen as Fuel for the Glass Industry, what are the Challenges?, Glass Problems Conference, 1-4 November 2021, Columbus (OH), USA
- Sander Gersen and Oscar Verheijen, Hydrogen as Fuel for the Glass Industry, what are the Challenges?, Glass International virtual event, 15-16 June 2021
- Oscar Verheijen and Sander Gersen, Hydrogen as Fuel for glass production, GOMD, 22-26 May 2022, Baltimore (Maryland), USA
- Oscar Verheijen and Sander Gersen, Hydrogen as Fuel for glass production, Furnace Solutions, 8-9 June 2022, St Helens, UK
- Oscar Verheijen and Sander Gersen, Technical aspects of combustion of natural gas –hydrogen blends, ICG 2022 –26th International Congress on Glass, 3-8 July 2022, Berlin (Germany)
- Oscar Verheijen, Hydrogen consortium plots industrial stage, Glass International April 2021, pp 20-21.
- Sander Gersen,: Hydrogen combustion research at DNV, Combustion institute Webinar https://www.youtube.com/watch?v=5FXO82etm0U
- Sander Gersen, ‘hydrogen as a fuel for heating processes, Hydrogreenn session (15-04-2021)
- Sander Gersen, "Toepassen van waterstof in hoge temperatuur industrie", TEG webinar (11-03-2021):
- N. Marcano, A. Ba, C. Guiberteau, J. Caudal, X. Paubel, L. Jarry, S. Gersen, B. Slm, R. Zeijlmaker, Air Liquide preparing burners for H2 transition in glass production’ Publication in the magazine Glass International March 2022
- https://www.dnv.com/article/hydrogen-as-a-fuel-for-high-temperature-heating-processes-219385
- S. Gersen, Pitch waterstof innovatie- en netwerkmiddag RVO, 21 april 2022

11 FINANCIAL AND PLANNING SUMMARY PROJECT

Planning

All project deliverables have been successfully delivered as agreed upon. However, the project faced some delays during the execution of the project. The main reason for the delays was the worldwide COVID-19 pandemic and quarantine restrictions. As a result the burners needed for the test could not be delivered on time as planned and we faced some delays in the supply of materials. Furthermore, the experts needed to witness and assist with the burner test were not allowed to travel.

Financial summary

The project is executed according to the estimated budget. Due to the faced delays more hours were spent on the project. However, we managed to reduce the material costs by for example efficient use of fuel gases. Full financial details have been provided to RVO and EY for an accountant statement.

About DNV

DNV is the independent expert in risk management and assurance, operating in more than 100 countries. Through its broad experience and deep expertise DNV advances safety and sustainable performance, sets industry benchmarks, and inspires and invents solutions.

Whether assessing a new ship design, optimizing the performance of a wind farm, analyzing sensor data from a gas pipeline or certifying a food company's supply chain, DNV enables its customers and their stakeholders to make critical decisions with confidence.

Driven by its purpose, to safeguard life, property, and the environment, DNV helps tackle the challenges and global transformations facing its customers and the world today and is a trusted voice for many of the world's most successful and forward-thinking companies.