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DECARBONISATION OF GAS TURBINES WITH THE H2R® HYDROGEN RETROFIT BURNER

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ABSTRACT

The 'H2R® burner' is a 100% hydrogen-capable retrofit combustion system for gas turbines. This solution allows installed gas turbines to continue operation in their existing infrastructure and, as the fuel composition evolves, to be ready for CO2-emissions free operation. The H2R® is intended to operate with Natural Gas and Hydrogen in any proportion, and therefore supports the energy transition.

The burner is a retrofit multi-tube cluster burner, scalable to target engines' capacity and thermal power. Given its inherent modularity, it can accommodate a variety of fuels and inert fluids. Eight variants of prototype burners have been developed and tested in an atmospheric rig particularly suited to the validation of gas turbine burners. Very low emissions have been achieved at all fuel compositions, and for a wide range of firing temperatures. Low emission levels at engine-relevant pressures are estimated, thereby fulfilling the current and expected future emission regulations. Dedicated flashback tests have been conducted, highlighting the good flashback resistance of the burner concept.

An overview of the burner validation results, the operational capability and overall current status is provided. Exemplary adaption of the H2R® concept to a target gas turbine is briefly described.

INTRODUCTION

Given their high load flexibility and fast ramp-up capability, gas turbines play a key role in the balancing and stabilization of the grid in Europe, as well as in gas transmission systems and decentralized power units. The demand for clean and low-carbon energy, however, increases significantly, and as the market share of renewable - but variable - energy rises, the capacity of hydrogen as a storage medium for excess renewable energy is coming increasingly into focus. Its use as a fuel in existing deployed gas turbines, first within existing natural gas infrastructures and distribution network, or natural gas / hydrogen fuel blends during a transition period, later running on hydrogen pure as a primary fuel, would enable the extended utilization of gas turbines while supporting the global decarbonization. Natural gas burning gas turbines - ~3400 in Europe - produce around 1150 Mt CO2/year. Converting a third of the installed fleet to hydrogen operation would already lead to an average of 390 Mt CO2 savings per year.

Many OEM companies of gas turbines have identified the opportunity of developing the capability of hydrogen combustion for gas turbines, and have therefore initiated hydrogen programs, aiming at extending the fuel flexibility of their new offerings, and in particular, increasing progressively the allowable amount of hydrogen in the fuel mix that new GT ratings can safely operate on (e.g., ETN Global, 2020). Dedicated research and development effort is concentrated on the improvement of existing combustion technologies, which enables the extension of today's hydrogen capability, at around 30 vol-% of hydrogen in the fuel, to a 50 / 60 vol-%. Higher hydrogen contents typically require the development of new technologies which mark a different conceptual approach to the design of GT burners (e.g., Noble et al., 2021).

H2R® is the hydrogen renewal burner for gas turbines operating currently on natural gas. The burner, which can be integrated into a variety of gas turbine architectures - aeroderivative, industrial or heavy duty gas turbines, silo, annular or cannular combustion chambers - can convert most gas turbines to zero carbon emission systems when operated with 100% hydrogen. The H2R® operates with 100% Natural Gas right through to 100% Hydrogen, and in any proportion of either fuel, with Ultra Low NOx emissions, making it suitable for immediate application for NOx reduction and compliance, and also for decarbonisation as Hydrogen becomes increasingly available. Background information on the burner concept, tests, validation, and adaption to a target gas turbine are provided in the present paper.

NOMENCLATURE

CFD	Computational Fluid Dynamics
DLE	Dry Low-Emissions
GT	Gas Turbine
H2	Hydrogen
H2R	Hydrogen Renewal burner
NG	Natural Gas
OEM	Original Equipment Manufacturer

FUNDAMENTAL PRINCIPLES OF THE H2R®

Background

Gas turbine burners have been typically designed for operation on natural gases, i.e., blends of light hydrocarbon fuels and some inert fluids. The majority of gas turbine burners implemented in DLE combustion systems are swirl-type burners, wherein axial, radial, tangential or conical guide vanes imprint a swirling motion to the combustion air, while also providing fuel injection into the flowing air. Fuel-air mixing will be promoted by the high level of turbulence inside the swirling and turbulent flow as it proceeds along the swirler, while a vortex breakdown stabilization, initiated by the tangential momentum of the bulk flow at the burner discharge plane, will support the flame stabilization of the incoming mixture through recirculation of the flame products. These technologies are well suited to classical gas turbine fuels, given their relatively low reactivity.

The addition of hydrogen to natural gas has several consequences on the thermophysical properties of the fuel, its chemical reaction characteristics, and therefore on the flames' characteristics (Taamallah et al., 2015; ETN, 2022). Most notable feature of hydrogen-rich fuels is the high mass and enthalpy diffusivity. This promotes local reaction in corrugated flames and will therefore particularly sustain and enhance the propagation of the flame front. This phenomenon of preferential diffusion will be exacerbated in turbulent conditions (Lipatnikov and Chomiak, 2005), as typically observed in gas turbine combustion chambers. The propagation speed of a hydrogen flame is about an order of magnitude higher than that of a methane flame, impacting position, length and thickness of the flame front, which stabilizes closer to the burner exit. Furthermore, its increased propagation speed leads to an increased risk of flashback into the burner, due to local velocity defects, e.g., in the wake of the swirler vanes, to enhanced local and global flow instabilities, such as the Combustion-Induced Vortex Breakdown mechanism, or to local boundary layer flashback (Benim and Syed, 2015). Additionally, hydrogen has a wide flammability range and low ignition energy requirements, potentially leading to premature and unwanted flame initiation inside the burner.

Another key difference between natural gas and hydrogen flames is their respective heat of reaction. The highest flame temperature reached by a hydrogen flame across the equivalence ratio range can be close to 200°C hotter than that of a methane flame. Implications are two-fold: the integrity of the combustor and burner hardware must be ensured accordingly. This is particularly relevant to diffusion-type engines, but also to premix burners with diffusion-based pilot stages. Another consequence of the higher maximum flame temperature is the NOx production associated with hydrogen flames. Apart from the differences in 'premix NOx formation' of the two types of fuels (e.g., de Persis et al., 2019), and the issues related to biases in reporting of NOx emissions due to standard dry and referenced O_2 corrections (Douglas et al., 2022; Garan et al., 2023), the increased local flame temperature will impact the rate of NOx formation associated with diffusion main or pilot flames (e.g., Kroniger, 2019).

Special attention has to be paid to the design of hydrogen-capable burner, in order to provide a clean aerodynamics discharge characteristic, a low residence time within the burner to avoid premature mixture ignition, a good fuel-air mixing quality that minimizes the hot reaction zones, and a good control of the piloting region that ensures mechanical integrity of the burner hardware and limited NOx impact. It is therefore a very challenging task to extend the fuel flexibility of existing burners to achieve full hydrogen capability.

Cluster tubular burner

A common approach to tackle the challenges posed by the combustion of hydrogen in gas turbines is to decrease the characteristic scales of the burner, and therefore to distribute spatially the downscaled elements to maintain the required burner capacity. As the size of the fuel nozzles decreases, so does the residence time within the burner, reducing the risks of early ignition. Furthermore, the residence times within the flame and in the post-flame regions, wherein further fuel-air mixing still occurs, are reduced, so that the volumes of hot zones are minimized, and the NOx generation is more confined. This concept is at the basis of some hydrogen burner concepts which rely on diffusion combustion, and yet achieve moderate Nox emissions. The modular Lean Direct Injection concept for hydrogen combustion (e.g., Marek et al., 2005; Weiland et al., 2013), or the MicroMix combustor (Funke et al., 2019), for instance, rely on this approach wherein fast mixing of non-premixed flames is key to moderate NOx formation. Other conceptual burner designs rely on the large distribution of small-scale premix fuel nozzles, to achieve fuel capability while ensuring a low NOx operability (e.g., York et al., 2012; Cho et al., 2022).

The H2R® burner concept is a cluster of downsized tubular premixed jet burners. Injector size reduction is achieved by distributing the fuel nozzles over a multitude of small-scale jet burners, hereby tackling the main issues for hydrogen burners mentioned previously. As described in the next section, the flexibility in the design of the individual jets facilitates the integration of specific features across the cluster, in order to fulfil the several requirements of a low-NOx fuel flexible burner. Prototype H2R® burners of the first three generations are shown in Figure 1.

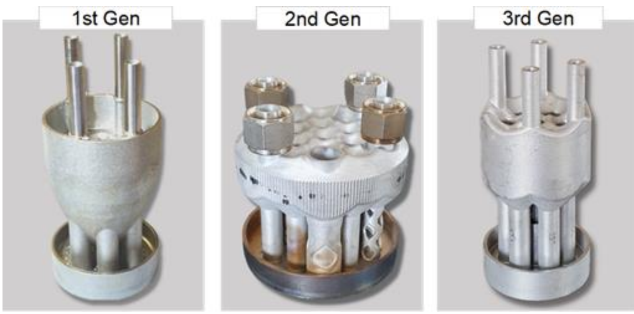
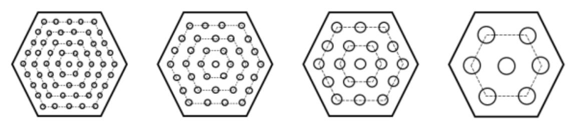


Figure 1: H2R® burner prototype hardware of the 1st, 2nd and 3rd generation

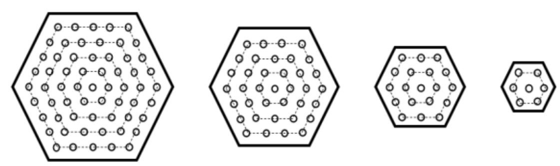
Modularity and scalability

The burner concept is modular by design. A stack-up of different modules, traversed by the multi-tube cluster of fuel nozzles, provides the necessary flexibility in integration required for the burner retrofit capability. Modules for cooling & dilution air are placed at the burner face and provide the necessary fluid plenum for cooling the burner front face and for flashback barrier measures. Premix fuel modules are laid out at the top of the burners, and provide the injection means to generate the premixed fuel-air mixture of the burner. The flexibility in the modular design allows for the integration of combined or separate natural gas / hydrogen fuel injection schemes, depending on the specifics of the target engine and site conditions. The modular design approach also permits an easy integration of fuel stages / pilot fuel modules, serving the purpose of operability and dynamics mitigation means. Furthermore, a steam module can be added for retrofit on older gas turbines using steam for power augmentation.

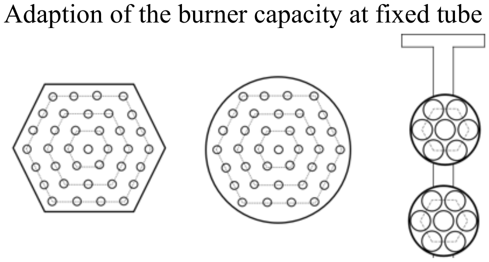
The multi-tube configuration of the burner offers great scalability for the development and adaption of the concept to specific configurations. For highly reactive fuels, a jet-flame is formed for each tube downstream of the burner. The distance of a tube to its neighbours is approximately the same across all tubes of the array, and similarity of the multiple flames is thus achieved, so that tube diameter and tubes density are the main design parameters for the burner. It is therefore possible, during the adaption of the burner concept, to size the burner tubes based on geometry and interface constraints, while keeping the intended burner throughput capacity. This scalability is illustrated in Figure 2a), where four different layouts of burners of the same capacity are schematically represented. Given the similarity of the individual flames' behaviour, scalability of the throughput can be achieved through adaption of the number of tubes across the burner, while keeping the characteristic tube dimensions equal and therefore the individual flames properties. The capacity and size of the cluster burner will be proportional to the number of tubular burners, making the adaption to a target thermal power a matter of adapting the tube count, Figure 2b). Further flexibility exists to adapt the burner layout to more specific geometrical configurations. While many burner-combustor interfaces are circular, some installations benefit from non-circular interfaces. Dry low-NOx combustion systems of silo combustor, for instance, rely on hexagonal multi-burner arrangements (e.g., Döbbeling et al., 2007). As illustrated in Figure 2c), the multitube arrangement of the H2R® allows the adaption of the layout to fulfil the requirements of the retrofit configuration.



a) Sizing of the tubes at fixed burner capacity



b) Adaption of the burner capacity at fixed tube sizes



c) Adaption of the burner to fit specific interfaces

Figure 2: Scalability and adaptivity of the H2R® burner concept to internal and external constraints (a), to target application capacities (b) and to specific interface conditions (c)

Prototype designs

Three generations of burners, as shown in Figure 1, have been developed, built and tested. All burners have been fabricated using additive manufacturing, enabling the inclusion of specific features in the design while reducing the number of process steps and manufacturing complexity. This sequence of burners permitted a systematic validation of the concept features: the first generation provided a proof-of-concept of the H2R® technology, showing the capability to operate on 100% hydrogen fuels while keeping NOx emissions to low levels. Other combustion performance parameters, such as Flashback, LBO and fuel flexibility already confirmed the high potential of the conceptual design. The three burners of the second generation permitted the verification of the burner modularity and scalability. Adaption to new interface conditions and increase in the throughput capacity were tested and confirmed the similarity of the burner performance when increasing the tubes density. Variants were built to examine the impact of different injection schemes on the mixing quality and emissions, and the interaction between injection schemes when operated simultaneously. The third generation of burners was developed to assess new injection and discharge schemes, which reduced the nozzle-to-nozzle fuel flow variability, and further improved the low-emission capability of the burner concept. Additionally, fuel-flexibility improvements were integrated in some prototype burners, by angling the tubes with respect to the burner axis. This supports the creation of a large and strong recirculating flow inside the combustor without the generation of a swirling flow inside the burner device (Kinoshita et al., 1997).

For the overall layout of the H2R® burner, design parameters of the multitube matrix burner, such as burner dimensions, tubes and injectors sizing, mixing length requirements, required throughflow characteristics, cooling air consumption and arrangement can be laid out from simple analytical considerations. Further refinement of the design parameters typically involves Computational Fluid Dynamics analysis (CFD) in order to refine the layout of the tubes' characteristics and arrangement, for the development of specific burner features, and for the integration of the burner in a given plenum-combustor configuration. Further CFD analysis are carried for the burner internal fuel and air paths and mixing. Detailed calculations are also used to support thermal state analyses of the burner, necessary for durability assessments.

As the burners were built using additive manufacturing, systematic characterization of the burner throughput capacity for the main and cooling air paths, and of the fuel injection variability has been performed for all eight prototype burners. Combustion experiments were then carried out in a dedicated rig, in order to assess the burner performance for pure hydrogen, pure natural gas, and for natural gas / hydrogen fuel blends. These will be presented in the next section.

ATMOSPHERIC VALIDATION OF THE H2R® BURNER

Burner flow characterization

The injection nozzles of the different burners have been integrated in the design for additive manufacturing of the parts, and no machining was intended nor performed on the fuel paths. Qualification of the injection methods were performed during the successive generations of burner models, from visual and water-flow characterization of coupons with representative injection nozzles, and through systematic flow-testing of the injectors of the prototype burners. Variability in the flow capacity of the injection nozzles can have a strong impact on the global tube-to-tube fuel-air uniformity, which impacts the burner performance, especially NOx emissions and flashback margins. Iterative improvements of the injection methods have been integrated in the designs to reduce this variability. Figure 3 shows the mass flow variability of the main injection schemes of the four burners of the 3rd generation. The latest injection methods show a 2.5% hole-to-hole standard deviation, corresponding to a variability of less than 0.015 in local equivalence ratio due to the fuel variability, equivalent to a standard deviation of less than 30K in local flame temperature. The single highest deviation measured reached a 4.2% deviation to the mean flow rate, i.e. a 50K local increase at the corresponding single jet flame front.

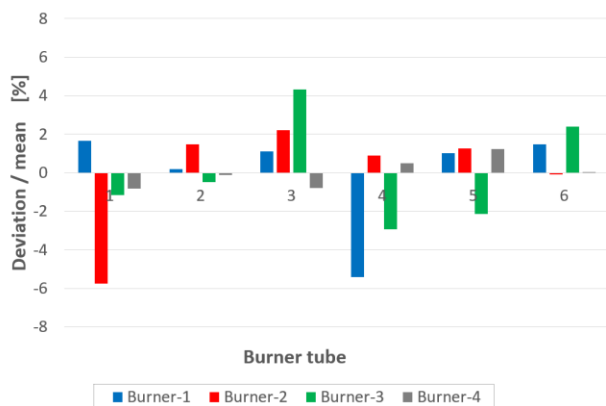


Figure 3: Injection mass flow measurements for 4 different burners of the 3rd generation

The influence of surface roughness on the burner pressure drop, mixing quality and flashback boundaries was also examined and quantified through back-to-back evaluation of 'rough' and 'processed' burners. No operational gain was achieved by processing and reducing the relatively low roughness already achieved in the additively manufactured prototype burners.

Combustion Validation Rig

Validation of the H2R® burner concept has been conducted within a test facility particularly well suited to the development and validation of gas turbine burners and combustor concepts (e.g., Winkler et al., 2017), schematically represented in Figure 4. Up to 80g/s of air can be preheated through a 55kW electrical preheater to generate temperature conditions representative of real gas turbine operation. After being used for reverse-flow cooling of the quartz flame tube, this air is discharged into a burner plenum wherein the majority is used as combustion air, and a portion is employed for cooling the burner and combustor front panels. Downstream of the flame tube, extraction of exhaust gas samples is performed for emission analysis.

Overall, a 100kW thermal power operation can be achieved, with a maximum hotgas temperature of 2000K.

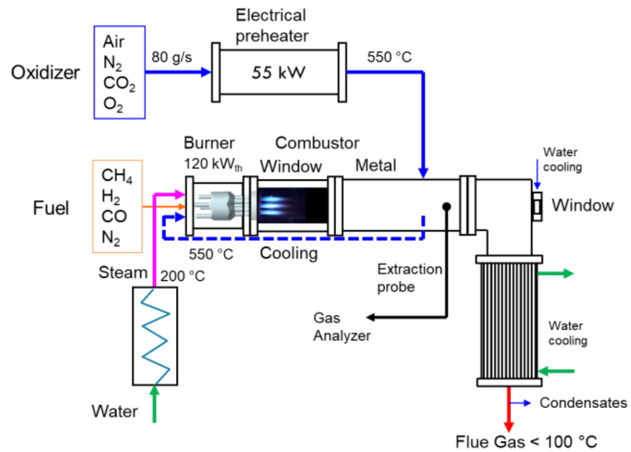


Figure 4: Arrangement of the atmospheric burner combustion test rig

The rig has several visual access points to enable extensive characterization of the combustion process, flame shape and flame-to-flame interaction, and to facilitate the characterization of burner flashback limits. The burner plenum is made of a quartz window, to provide visual access to the "cold side" of the burner during operation. As mentioned previously, the flame tube and flow sleeves are also made of quartz windows, thereby allowing side-view of the flame fronts. Standard visualization of the flame fronts for hydrogen and natural gas operations is illustrated in Figure 5, from the side windows of the test rig. OH* chemiluminescence analyses of the reaction zones have also been performed, using the visual access offered by these side windows, as illustrated in Figure 6. Back view towards the burner front face is also available, to assess ignition, flashback, and front face thermal state. Fuel supply is quite flexible, as pure fuels and fuel mixtures can be supplied to the burner. In the present validation exercise, pure natural gas, pure hydrogen as well as mixtures of these two fuels were used.

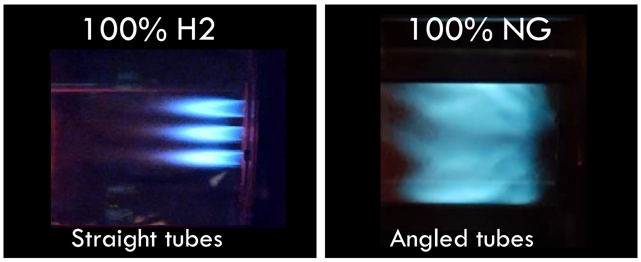


Figure 5: Visualization of flame fronts from two H2R® burners of the third generation, operated at a flame temperature of 1950K, on pure hydrogen (left) and pure natural gas (right).

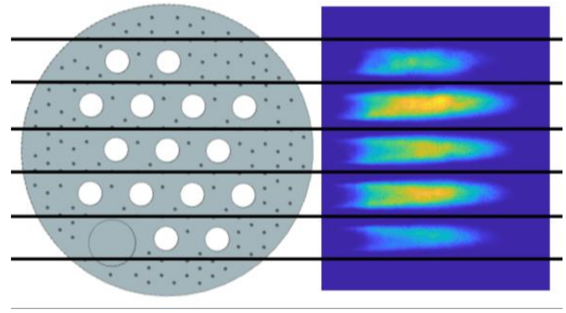


Figure 6: Field of view alignment and exemplary result of an OH* chemiluminescence visualization for an H2R® of the second generation operated at 1950K flame temperature on pure hydrogen

Burner Performance

The results of the tests conducted on the 3rd generation of burners are hereafter presented. The behaviour of the burners for varying throughputs is presented first, showing the wide pressure drop window of operation of the burners. Flashback resistance and lean limit on natural gas are discussed afterwards. The burner capability over varying fuel mixtures is finally discussed.

<u>NOx for different burner throughputs</u>

The flow capacity of the H2R® burners has been tested at different fuel compositions. Figure 7 shows the impact of the burner pressure drop on the NOx emissions, for air preheated to 400°C, pure hydrogen and pure natural gas, and a burner with angled tubes. The throughput variation is achieved by varying air and fuel flows across the burner, keeping the combustion temperature constant, such that burner thermal power and heat load change during the pressure drop variation.

Operation with natural gas will normally be limited by the lean operability of the burner. In particular, as the throughflow is increased, flame loss is expected to occur: as the discharge flow velocity goes up, the shear stresses at the root of the flames increase and the stabilization mechanism of the jet flames becomes weaker. The H2R® burner could be operated on natural gas at a firing temperature of 1750K, i.e., a temperature representative of typical gas turbine conditions, over a range of pressure drops, exceeding 6.5%, well above the expected operating condition of a DLE burner in typical gas turbines. CO emissions remained lower than 1ppm until a pressure drop of 6.5% was reached, where the emissions started rising, indicating weakening of the flame stabilization.

Lower pressure drops pose no particular challenge to the burner operation on natural gas and were thus not extensively mapped. Hydrogen flames, on the other hand, have an increased stability compared to natural gas, and their operational challenges will occur at high temperature conditions and low burner pressure drops: the burner throughflow can reach a critically low velocity and lead to the occurrence of flashback. Figure 7 reports burner emissions for operation on pure hydrogen, at a combustion temperature of 1950K, i.e. at operating conditions more challenging than standard gas turbines, reaching pressure drops below 1%, below the characteristic pressure drops of typical gas turbines.

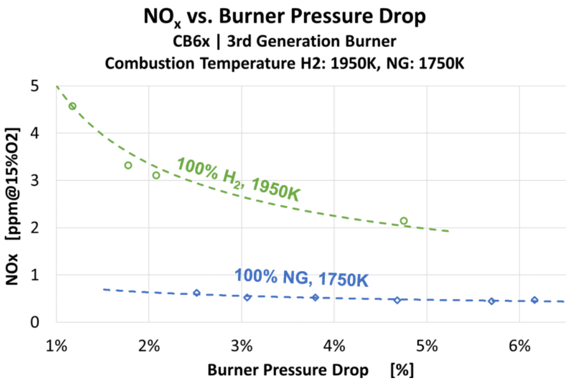


Figure 7: Range of burner pressure drops over which H2R® could be operated. Air temperature: 400°C. Green: pure hydrogen, blue: pure natural gas. Unpiloted operation

Both operations on natural gas and hydrogen show a similar trend of reducing NOx emissions as the burner pressure drop increases. This effect has been observed and reported before and has been explained in light of the increased strain rate on the flame stabilization and reaction zone (Syed et al., 2007). As noted above, higher burner throughflows come with higher shear stresses along the discharge jets of the burner flow and the stabilization at the flame root is weakened. Furthermore, turbulent propagation of the flame against the higher flow velocity is reduced. OH* chemiluminescence visualizations of the flames, as illustrated in Figure 6, were carried during the tests, and the effects of burner throughput on the flames' stabilization could thus be observed. Both flame lift-off and flame length increase with the increase in burner throughput. Doubling the burner pressure drop leads to a 20% increase in lift-off height and a further 30% increase in flame length, such that the mixedness at the flame front and in the post-flame region improves with the increase in fuel-air mixing distance. Furthermore, higher flow rates decrease the post-flame and total residence times, which will in turn reduce the thermal NOx production of the flame. All these effects can justify the observed decrease in emissions with pressure drop.

Flashback resistance

Resistance of the H2R® burner concept to flashback events was also quantified through variations of the burner throughput. The burners were run stably at GT representative conditions, and the burners throughflows were reduced, keeping the flame temperature constant, until flame flashback was detected. Figure 8 shows the results of such forced flashback tests for two H2R® burners with straight tubes of the third generation, running on pure hydrogen. As reported earlier, a reduction in burner throughput comes with a reduction in the flame lift-off distance. As the flame approaches the burner front face and the burner tube velocity decreases, flashback eventually occurs. Aside from the visual observation, flashback events could be systematically detected by the appearance of high-frequency dynamics. Flashback limits at atmospheric conditions and 400°C air temperature were only quantified for pure hydrogen, as low as 0.35% pressure drop for the burners with straight tubes of the third generation.

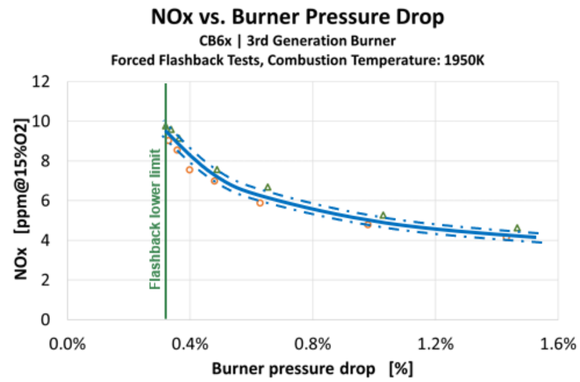


Figure 8: NOx variation against burner pressure for two burner variants of the third generation (symbols) and corresponding trendline. Air temperature: 400°C, pure hydrogen, combustion temperature of 1950K

Extensive testing of flashback boundaries has been carried out during the validation of the H2R® burners of all generations. The dependency of this operational limit on injection schemes and other burner attributes was quantified, as well as the influence of preheat temperature. The latter impacts the mixture reactivity, the burner metal temperature as well as the thermo-physical properties of the fuel-air mixture, all of which will influence the flashback margins (Kalantari and McDonell, 2017). A 15% relative reduction in burner pressure drop at flashback conditions for a 50K decrease in the preheat temperature was measured. Similarly, higher combustion temperatures lead to increases in the mixture reactivity and in the heat load to the burner front face. In this case, a 10% relative reduction in burner pressure drop at flashback conditions for a 300K decrease in the combustion temperature was captured. Given the low flashback propensity of the H2R® burners, there is a great flexibility and freedom to optimize the burners while adapting the concept to specific retrofit engines and their specific operation conditions, whilst keeping a large flashback margin for safe operation.

Capability on natural gas

At throughput conditions representative of typical gas turbine conditions, natural gas operation has been extensively tested. Figure 9 shows the emissions of a burner of the third generation operated on pure natural gas, unpiloted, at a preheat air temperature of 400°C, and for a range of combustion temperatures. At higher temperatures, NOx emissions remain very low, not exceeding 1.2ppm to 1950K. The emission analysis system does not capture equilibrium CO at high combustion temperatures, without impact on the burner performance assessment. As the temperature is decreased, NOx emissions decrease as expected, and CO increases mildly down to 1650K, and shows a steeper increase for combustion temperatures below 1625K. Further extension of the CO compliance window was achieved through piloted operation.

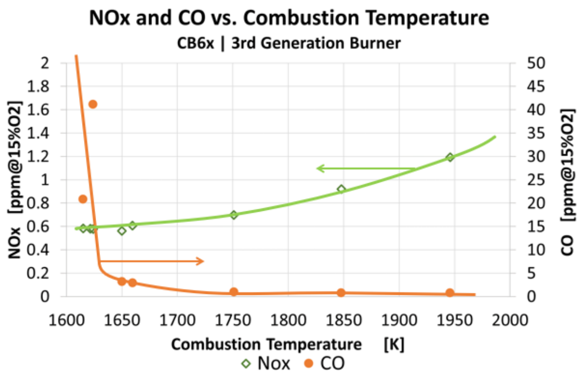


Figure 9: H2R® burner operation on natural gas: NOx and CO emissions vs. combustion temperature, unpiloted

Fuel Flexibility

Operation of the burner on pure hydrogen and pure natural gas is demonstrated and shows a wide operational window around typical gas turbine burner operating condition. Figure 10 shows the NOx emissions of an H2R® burner of the 3rd generation for a variety of natural gas / hydrogen mixtures, and at combustion temperatures of 1750K and 1950K. No discernible variation in the NOx emissions occur until a hydrogen ratio of 50% by volume. As the fuel reactivity is increased, beyond 50 vol-%, the flames shorten further, and the NOx emissions increase in an almost linear manner. The biases in NOx emissions due to standard dry and reference O_2 corrections (Douglas et al., 2022; Garan et al., 2023) apply to these figures, as the emissions are reported for a 15% O2 correction. Nevertheless, the emissions remain very low for both combustion temperatures.

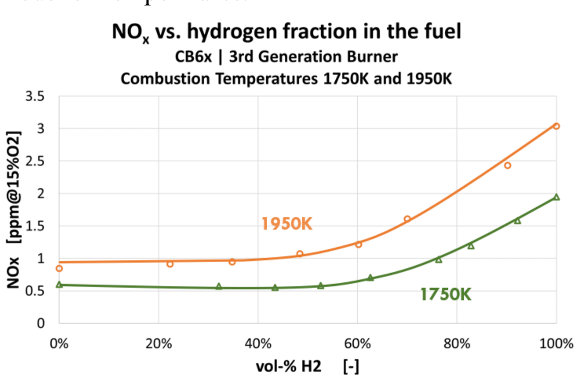


Figure 10: NOx variations of the H2R® burner for varying hydrogen proportions in the fuel mix. Air preheat temperature at 400°C. Combustion temperatures of 1950K (Orange) and 1750K (Green).

Apart from high-frequency dynamics indicators of flashback events, no combustion dynamics were observed during the atmospheric tests for any condition. For thermoacoustic control during the implementation to a specific configuration, the burner concept itself offers a large flexibility of mitigation measures. The absence of swirl convection inside the burner alleviates a mode of instability coupling, making the burner less prone to dynamics instabilities. Furthermore, the time-lag that separates the fuel injection location from the flame front is a key parameter to the characteristics of dynamic response of a flame front. The multitube design allows a straightforward adaptation of the injection locations, and spread thereof, supporting a reduction in the risk of dynamic coupling (Krebs et al., 2022). Moreover, a multitube design relies on a spatial distribution of individual burners, so that internal staging can be easily applied to mitigate combustion dynamics. Radial staging, for instance, has been shown to successfully support the control of combustion instabilities in laboratory cluster burners (Kang et al., 2021).

ENGINE CONFIGURATIONS

The H2R® burner technology is being adapted for retrofitting in a target gas turbine combustor. Projected burner performance at the specific operational conditions of the turbine and configuration of the burner to fit the GT interfaces have been assessed and are described hereafter.

Projected figures at high pressure

The burner performance obtained at atmospheric conditions have been projected to the specific operational conditions of the gas turbine, indicating the capability for the combustion system to operate at low NOx emissions, for pure natural gas, pure hydrogen, or mixtures of these fuels. Pressure in particular influences the formation of NOx emissions. While the 'in-flame' NOx production is reduced through pressure increase, the 'postflame' formation mechanism increases significantly, and its dependency is typically modelled as a pressure exponent. While exponents of the order of 0.5 – 0.67 can be found in the literature for premixed burners (Biagioli and Güthe, 2007; Han et al., 2014), an exponent of 0.7 is used to estimate the NOx emissions at engine relevant pressures, to further account for the impact of piloting on the overall NOx production (Han et al., 2014). Given the scarcer amount of literature on the pressure dependency of NOx emissions for pure hydrogen flames, the same extrapolation models as for natural gas fuels has been employed. Figure 11 shows the trend of NOx emissions as a function of the combustion temperature based on the acquired atmospheric data and extrapolated to the target engine pressure at baseload of ~9bar. Operation on natural gas leads to extremely low emissions, while hydrogen operation is expected to remain at single digit conditions for combustion temperatures up to 1800K.

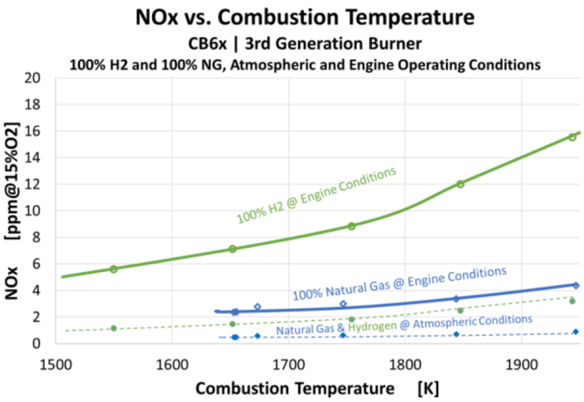


Figure 11: NOx variations of the H2R® burner vs combustion temperature at atmospheric conditions, obtained from experimental validation tests, and extrapolated to engine relevant pressure conditions

The impact of pressure on the flashback boundaries have also been considered and assessed. The experimental configuration employed by Kalantari and McDonnel (2017) to establish their prediction correlation relies on premixed jet flames and shares therefore similarities with the H2R® burner concept. The Damköhler correlation for flashback limits has been anchored onto the atmospheric results and applied to assess the impact of pressure, air temperature and combustion temperature on the flashback limits at the target gas turbine conditions. At baseload, the pressure drop over the burner at design throughput conditions is more than 35% higher than the predicted flashback limits.

Adaption to target engine configuration

The H2R® burner concept has been adapted for implementation in the cannular combustor of an existing gas turbine. The target gas turbine was chosen as it operates in markets where hydrogen combustion is likely to occur early in an emission constrained future. A representation of the H2R® burner integration in the combustion system of the target engine is provided in Figure 12. A combustor air and thermal flow model has been created to represent the complete combustion system, and applied to both cases of natural gas and hydrogen operation. Primary flows were allocated to the main burner path, the cooling air and the dilution air for the management of the required turbine inlet temperature and temperature profiles.

Figure 13 shows the corresponding H2R® burner, scaled to accommodate the required throughput capacity of the system, and adapted to fit the geometrical interfaces of the engine. The sizing of the tubes numbers and dimensions ensures the provision of the primary combustion air flow and the intended combustion temperature for a stable a low-NOx operation. The burner geometry was developed using the air flow split model, including cooling flows to the burner front face, while ensuring the fulfilment of combustion performance and operational safety requirements.

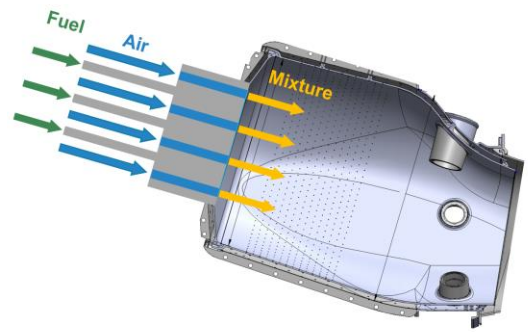


Figure 12: Representation of the H2R® burner in the target cannular combustor

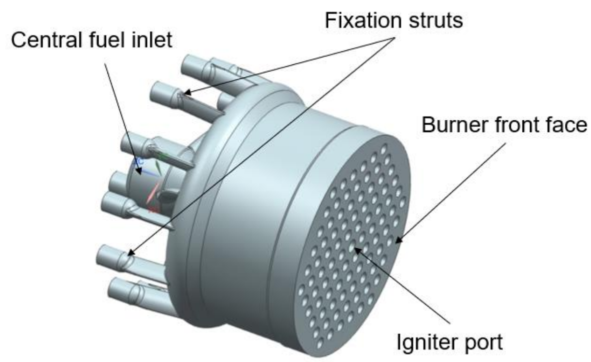


Figure 13: Model of the adapted H2R® burner

To support the adaption of the burner to the specific conditions of the target configuration, Computational Fluid Dynamics (CFD) calculations were undertaken, using the ANSYS Fluent software, to model the flow in the combustor from the burner exit through to the turbine inlet plane. Some of the simulations conducted during the layout of the burner are hereafter described. Several cases were simulated, with variations in the fuel composition (100% Hydrogen and 100% CH4), and piloting ratios. Figure 14 to Figure 17 show some key results of the numerical investigation for the unpiloted cases. As expected, flames are shorter with hydrogen than with methane as a fuel. However, the general flame behaviour appears to be similar, demonstrating that the H2R® burner-combustor combination is calculated to be capable of burning both fuels in a similar manner within the same hardware. The CFD results were used to estimate the NOx emissions for the combustor at full load, provided in Table 1.

Table 1: Estimated NOx emissions from the CFD calculations

ppm dry 15% O2	CH4	H2
Total NOx	3.4	14.9

While the absolute levels of the calculated NOx emissions should be validated by testing, the calculated trend matched closely the empirically extrapolated data of Figure 11, with single digit NOx values for pure methane and less than 15ppm for pure hydrogen, and are thus expected to be realised, and the emissions of the combustion system are expected to be compliant with regulations for natural gas, hydrogen, and any mixture of these fuels.

Furthermore, complete combustion was achieved upstream of the dilution jets, such that no reaction quenching occurs. Carbon Monoxide CO emissions at lower loads, where the CO is expected to be highest, was not estimated from the CFD due to the large uncertainties in the modelling of low Damköhler flames and to the challenge in modelling accurately CO emissions. Testing, rather than CFD, will be relied upon for the evaluation of CO emissions at lower engine loads.

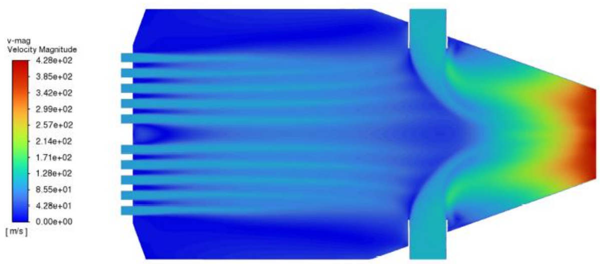


Figure 14: CFD simulation of the adapted H2R® burner in the can combustor - 100% CH4, field of velocity magnitude

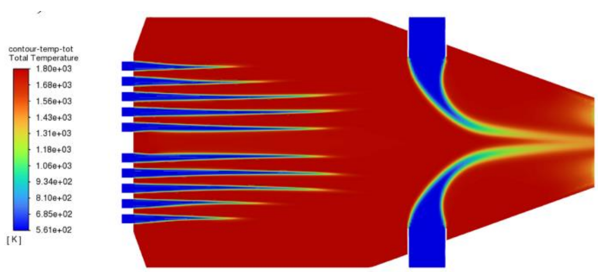


Figure 15: CFD simulation of the adapted H2R® burner in the can combustor - 100% CH4, field of temperature

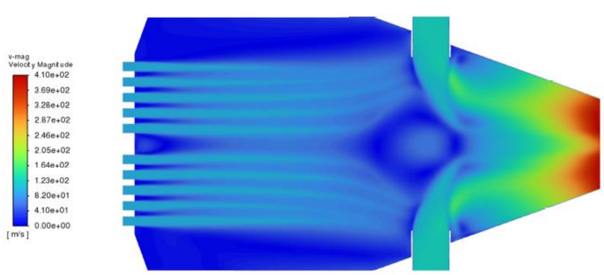


Figure 16: CFD simulation of the adapted H2R® burner in the can combustor - 100% H2, field of temperature

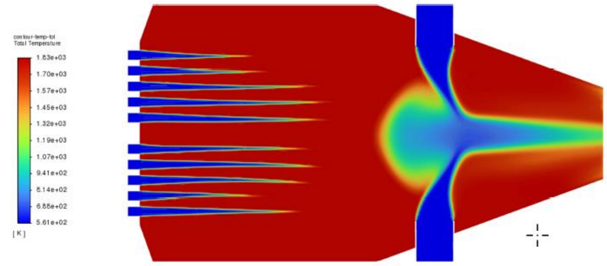


Figure 17: CFD simulation of the adapted H2R® burner in the can combustor - 100% H2, field of temperature

CONCLUSION AND NEXT STEPS

The H2R® burner has been developed as a retrofit solution to permit gas turbine operation on Natural Gas, Hydrogen and any mixture thereof, using the same hardware. Testing has been used for the proof of concept of the H2R® technology, and to further develop and optimise features of the burner. With a verified scalability to various throughputs, geometry and operating conditions, the burner concept can be adapted to different engine configurations. Such an adaption is shown in the paper, where scaling of the burner is applied to match the requirements of a selected gas turbine combustor. CFD calculations have been employed to assess the discharge characteristics and flowfields inside the combustion chamber, enabling the verification of the fuel flexibility of the combustion system. Calculated NOx emissions from these computational results are in line with expected emission levels from extrapolated test results, and are compliant with regulations for both natural gas and hydrogen fuels.

High-pressure validation of the H2R® will be conducted, to confirm the low-emission capability of the burner concept on a variety of fuel compositions, and the safe operability at engine relevant operating conditions. In parallel, testing of the full can configuration with the final adaption of the H2R® for the target combustor will be conducted for further validation and information on the operability and CO capability of the combustion system. Additional adaptions of the H2R® technology to other Gas Turbines are currently underway.

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