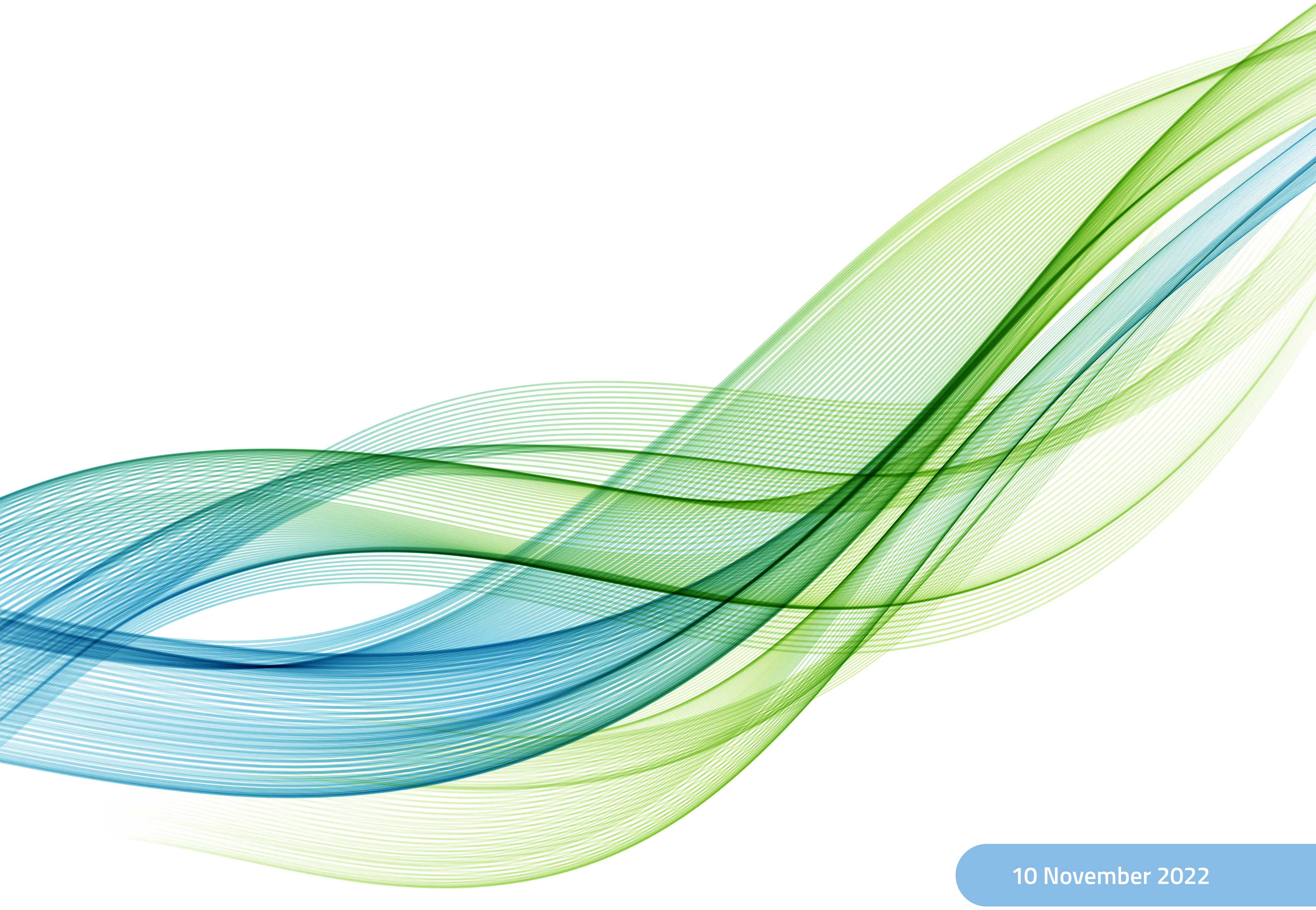
ETN
Global

ADDRESSING THE COMBUSTION CHALLENGES OF **HYDROGEN ADDITION TO NATURAL GAS**: SUMMARY REPORT



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1. Introduction

To achieve the rapid transformation of the European (or any other) gas and electricity grids into renewable-based energy systems will require many technical challenges to be overcome. Electricity Grid balancing and stability support are two of those challenges in which gas turbines already fulfil a crucial role. Energy storage to prevent curtailment of excess renewable generation is another challenge that could be supported by using green hydrogen as a storage medium. Additionally, the generation of low-carbon hydrogen could provide a source of low-carbon fuel. By extending the fuel capabilities of gas turbines to blends of natural gas and hydrogen (up to 100% hydrogen), they could play a major role in the energy transition period and also in the long-term future of low-carbon energy generation.

There are significant combustion challenges involved in the implementation of hydrogen gas turbines, one of which is the potential for increased levels of nitrogen oxides (NOx) emissions. This position paper was initially prompted by the simple question posed to the ETN Hydrogen Working Group: "Is there any fundamental reason why a well-optimised hydrogen flame should produce more NOx than a natural gas flame with the same flame temperature?". This generated the additional question "What are the fundamental differences, from a combustion perspective, between natural gas and hydrogen?"

A technical report [1] was produced, bringing together the experience and knowledge of ETN members to answer these questions as far as possible. It reviewed fundamental aspects of natural gas/hydrogen combustion and identified their impact on combustion and flame characteristics. It also considered the practical implications for gas turbine operation and identified the impact on key combustion performance indicators such as emissions.

This report summarises the findings of the study and outlines its conclusions and recommendations to facilitate the introduction of gas turbines firing the full range of hydrogen and natural gas blends to deliver low-carbon power and heat.

2. Impact of hydrogen in natural gas on combustion behaviour

2.1. Fundamentals

Blending hydrogen into natural gas will progressively change mixture properties, but the relationships are not linear, for example the energy content (LHV basis) in a mixture of hydrogen and methane as a function of hydrogen content is shown in *Figure 1*. It can be seen that when the hydrogen content in the blend is 40vol%, the hydrogen contributes less than 20% of the energy to the mixture. An understanding of the impact of fundamental properties and behaviour of blends of methane (or natural gas) and hydrogen over the full range of 0 to 100% hydrogen is needed to allow any fundamental limitations and difficulties associated with using increasing levels of hydrogen in gas turbines to be well defined.

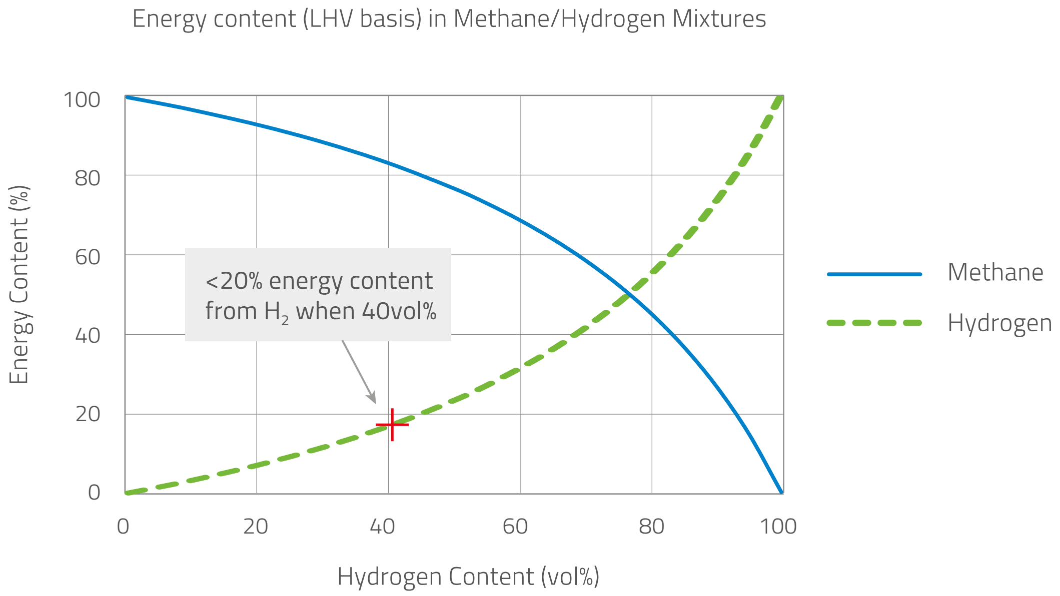

Figure 1. The energy content contributions of methane and hydrogen in blends

An understanding of the detailed chemical kinetics of combustion chemistry is needed to evaluate key fundamental properties such as, flame speed, flame temperature and autoignition temperature and delay time. Chemical kinetics also play a key role in the formation of pollutants such as NOx.

Chemical kinetic schemes or mechanisms consist of a series of chemical reactions that, together with the relevant data for each reaction, can be used to describe the overall (or global) reaction that occurs during combustion. Typically, several hundred reactions are required to describe the chemical process occurring during combustion and a range of chemical kinetic schemes has been developed. There is still uncertainty as to the best approach to describe all the required properties across the full range of natural gas blends with hydrogen. However, existing mechanisms including GRI Mech 3.0 [2] Konnov [3], Glarborg [4] and AramcoMech 1.3 [5] can provide useful insights into fundamental properties such as adiabatic flame temperature, laminar flame speed and autoignition delay time, and further development and validation is needed to improve confidence in predicted trends.

The adiabatic flame temperature for a fully premixed air-fuel mixture varies with equivalence ratio and much of the published combustion information is presented as a function of equivalence ratio. However, from a gas turbine control perspective, the mixed-out flame temperature (i.e. the turbine inlet temperature) is usually more relevant than the equivalence ratio. Because the adiabatic flame temperature as a function of equivalence ratio is different for natural gas and hydrogen, the comparison of published data for methane/natural gas, hydrogen and blends needs to be treated with caution. For example, the main report [1] shows under the conditions typical of gas turbine combustion (16bara, 723K mixture inlet temperature), natural gas firing with an equivalence ratio of 0.6 would result in an adiabatic flame temperature of 2000K, whereas to achieve the same flame temperature with hydrogen would only require an equivalence ratio of 0.52 and for a given equivalence ratio, the flame temperature will be significantly higher for hydrogen than natural gas.

Flame speed depends on a wide range of factors and typically two types of flame speed are considered, the laminar flame speed and the turbulent flame speed. The laminar flame speed is the speed of the flame for perfectly mixed reactants under ideal laminar flow conditions. It depends on the composition of the fuel-oxidiser mixture and the temperature and pressure of the mixture prior to ignition and can be calculated using detailed chemical kinetics. Some low power applications use laminar flames, but in practical high-power systems such as gas turbine combustion systems, there is not an ideal laminar flow-field and the flame speed under turbulent conditions has to be considered. The turbulent flame speed is a function of the laminar flame speed, but also depends on the behaviour of the fuel in the turbulent flow field. The main report [1] shows that at low hydrogen concentrations, trends in turbulent flame speed follow those of the laminar flame speed that can be calculated from detailed chemical kinetics. However, at higher hydrogen concentrations (above about 20vol% depending on equivalence ratio) the difference in physical properties of hydrogen such as diffusivity and thermal conductivity have a dominant effect on turbulent flame speed which no longer follows the trend of laminar flame speed. Variation in turbulent flame speed with both hydrogen content and equivalence ratio were found to be particularly rapid at hydrogen contents above ~30vol% making combustion design particularly challenging when hydrogen concentration or equivalence ratio vary at higher hydrogen concentrations.

In addition to the impacts on turbulent flame speed, the differences in physical properties between natural gas or methane and hydrogen have a significant impact on combustion system behaviour, for example, to achieve the same energy input as a methane flame, a methane/hydrogen blend requires a much greater volume of fuel due to the lower volumetric heating value of hydrogen (Lower heating values at 20°C and 101.325kPa: methane = 33.36MJ/m^3, hydrogen = 10.05MJ/m^3). This significantly increases fuel jet velocities and this affects the way in which the air and fuel mix. Fuel injection systems optimised for natural gas will not be optimised for hydrogen and fuel placement and mixing will depend on the hydrogen content in blends.

2.2. Impact of fundamentals on combustion characteristics

The fundamental chemical and physical differences between methane and hydrogen will have a significant impact on flame behaviour and combustion characteristics. Four key performance indicators for combustion systems are combustion efficiency, NOx emissions, thermoacoustics and flashback potential.

An indicator of poor combustion efficiency in natural gas combustion is increased emissions of CO and unburnt hydrocarbons (UHCs) and all gas turbine combustion systems have been developed for high combustion efficiency (low CO and UHC emissions). CO and UHCs only become an issue at low equivalence ratios (low flame temperatures) which typically only occur at low gas turbine power. Hydrogen addition tends to reduce the flame temperature at which combustion efficiency issues occur improving low load CO and UHC emissions when burning natural gas/hydrogen blends.

NOx emissions are normally specified in ppmv or mg/Nm^3 corrected to 15% O_2 and dry conditions. The different oxygen consumption and water production in hydrogen combustion results in different combustion products to those for natural gas. The main report [1] shows that the corrections to 15% O_2 dry result in the NOx output from hydrogen combustion being apparently 36.4% higher than from methane combustion producing the same number of moles of NOx. For example, if for methane combustion NOx is 25.0mg/Nm^3 (dry, corrected to 15% O_2) and combustion of hydrogen to produce the same amount of thermal energy produces the same number of moles (and same mass) of NOx then measured NOx would be 34.1 mg/Nm^3 (dry, corrected to 15% O_2). Other published works come to similar conclusions [6] [7].

It can be seen that permitted NOx emissions levels quoted on a dry basis corrected to 15% O_2 seriously disadvantage hydrogen even when the total mass of NOx produced is the same. Also, much published literature on NOx emissions is presented corrected to 15% O_2 dry and this should be taken into account when interpreting data. This is particularly important at high hydrogen concentrations.

When addressing the question that prompted this study: "Is there any fundamental reason why a well-optimised hydrogen flame should produce more NOx than a natural gas flame with the same flame temperature?", the work of Ciani et al [8] was considered. This appeared to show that there was a significant increase in NOx emissions for ideal premixed flame *(Figure 2 (left))*, however the results are plotted on a corrected basis in line with normal reporting of emissions for regulation purposes. When plotted on an uncorrected mass basis *(Figure 2 (right))* the picture is quite different, showing that at higher flame temperatures there is a modest decrease in NOx at high hydrogen concentrations, but at lower flame temperatures (1700K) these is a small increase (13% for 100% hydrogen).

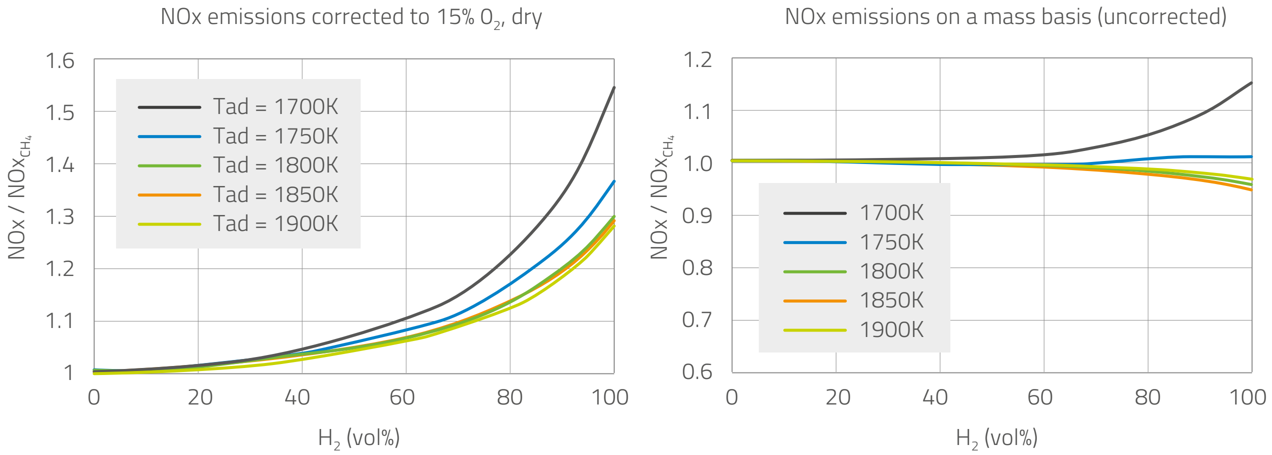

Figure 2. NOx Emissions in 1D unstretched laminar premixed flames normalized by NOx of the pure methane fuel case calculated using the Glarborg mechanism (residence time = 15ms, pressure = 20bara, reactant temperature = 450 °C)

Another recent study [9] calculated NOx emissions for an ideal premixed flame using GRI Mech 3.0 at a flame temperature of 1800K only and found a larger decrease in NOx (20% at 100% hydrogen). The two studies use different flame models and mechanisms, thus the difference in results is not surprising. However, both studies strongly suggest that for an ideal premixed flame increasing hydrogen concentration will not significantly increase NOx emissions and under some conditions there may be a decrease. This contrasts with both rig and on-engine tests of practical gas turbine burners which show a marked increase in NOx as hydrogen is added. *Figure 3* shows rig data for GE gas combustors (left) and on-engine data for a Siemens SGT-600 gas turbine (right). (N.B. this data has been corrected to 15% O_2, dry, in the usual way but as indicated in the left hand plot, the impact of this at these hydrogen concentrations is less than the scatter in the data).

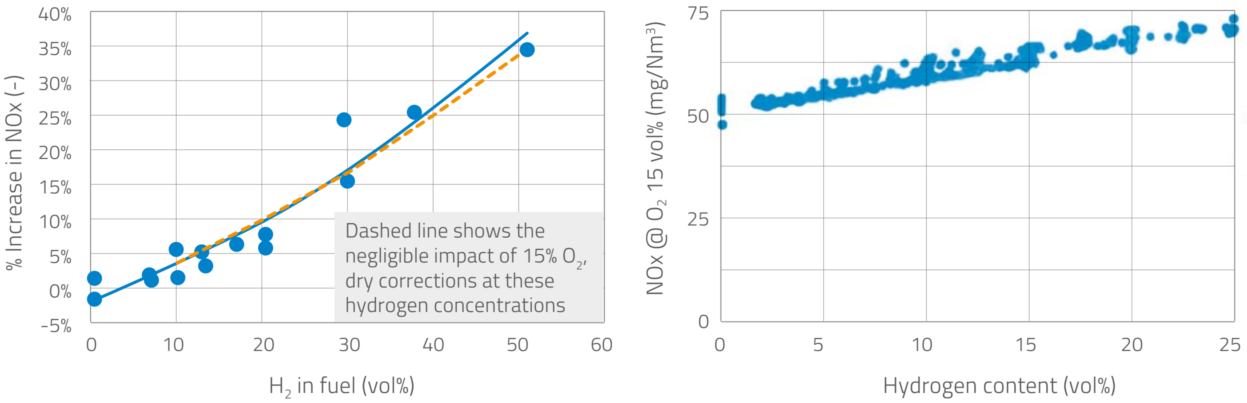

Figure 3. Left: Impact of hydrogen on NOx emissions from a gas turbine (based on preliminary laboratory data) (from [10])

Right: Emissions as a function of hydrogen content for an SGT-600 gas turbine operating at 25MW base load (modified from [11])

Laget et al [11] found that some of the increase in NOx occurring when hydrogen content was increased could be recovered by re-tuning the combustor. To accommodate variable hydrogen concentration and compensate for changes in emissions and thermoacoustics (high amplitude combustion driven pressure oscillations which can build to damaging levels) dynamic re-tuning would be beneficial.

The striking difference between the ideal and real combustor data emphasises the fact that factors other than chemical kinetics play a strong role in combustion behaviour including NOx generation. A significant factor in this is the increase in reactivity that occurs as hydrogen is added to the fuel mixture. This is illustrated by *Figure 4* which shows the impact of hydrogen concentration in the fuel on laminar and turbulent flame speeds. Both increase with increasing hydrogen content, the turbulent flame speed (relevant to gas turbine combustors) increases more rapidly than the laminar flame speed at higher hydrogen concentrations. In a practical combustor, as the turbulent flame speed increases, the flame tends to move upstream. This reduces the mixing time available before the flame resulting in poorer air-fuel mixing, increasing NOx emissions. Mixing may be made worse by the impact of hydrogen on fuel volume flows which increase for the same energy input and impact on fuel placement and mixing. The upstream movement of the flame increases the post-flame residence time also increasing NOx.

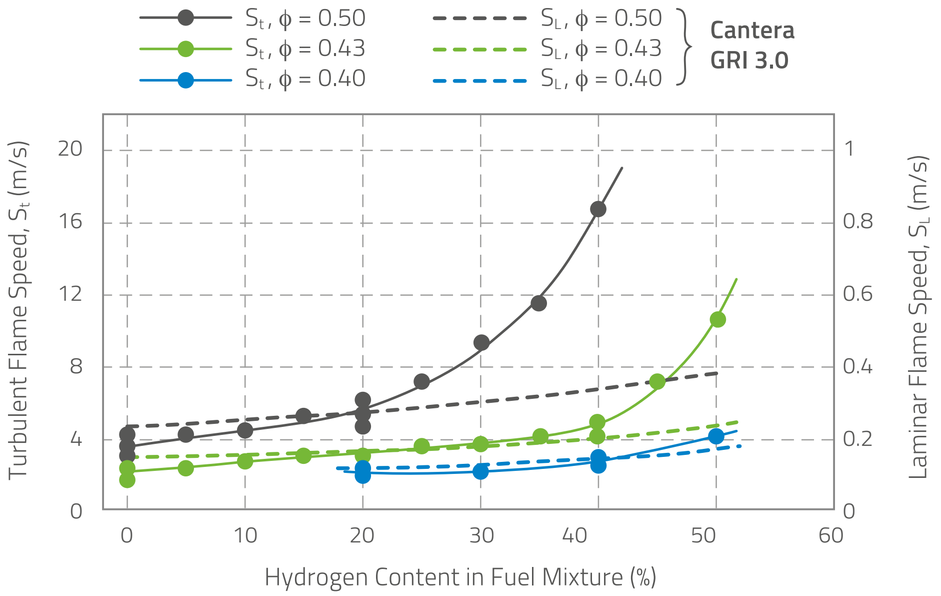

Figure 4. Turbulent flame speed data for methane/hydrogen fuel gas mixtures [12]

Current gas turbine combustors have been optimised over decades to produce low NOx emissions when firing natural gas and the impact of hydrogen on flame speed, mixing and fuel placement change the flame shape, position and temperature profiles. This impacts NOx emissions, thermoacoustics and flame stability. A significant amount of analytical and experimental effort will be required to optimise current combustions systems for a range of hydrogen blends and to develop alternative combustion approaches for high hydrogen combustion.

Gas turbine combustor tuning activities seek to find the optimum combustor performance while maintaining acceptable emissions and thermoacoustics. The introduction and development of new combustion technologies (including new fuels) always carries the risk of generating damaging thermoacoustic pressure oscillations. Whether damaging pressure oscillations occur depends on the acoustic characteristics of the flame and of the system that contains the flame. In a gas turbine, this system should be regarded as the whole of the air supply system and combustion system from the compressor discharge to the turbine inlet, together with the fuel supply system. The addition of hydrogen to the fuel has relatively little effect on the system acoustics, but impacts the flame behaviour through its impact on fuel supply acoustics and flame shape and position. In existing premixed systems, the flame will tend to become more compact if hydrogen is added, reducing characteristic flame times and tending to favour higher frequency modes. However, new and alternative technologies for high hydrogen combustion will face new thermoacoustic challenges and a greater understanding thermoacoustic modelling and experimentation is required to facilitate the utilisation of hydrogen and hydrogen natural gas blends.

Flashback is a major concern for premixed combustion concepts when firing high hydrogen blends because of the increase in reactivity as illustrated by the increase in turbulent flame speed (*Figure 4*). The main report [1] discusses this in detail and concludes that rig tests show that there is the potential for flashback in lean premixed burners when firing high hydrogen fuels. However, there is limited on-engine hydrogen testing to confirm this for real burners in service. Risk can be reduced by increasing mixture flow velocities, but this has a significant adverse impact on efficiency. The development of flashback resistant burners for high reactivity fuels (high C2+ plus hydrogen) is the result of decades of optimisation and significant development effort will be needed to produce robust flashback-resistant versions of both existing and new combustion concepts for even higher reactivity fuels with increased levels of hydrogen content.

2.3. Combustion technologies

There are many combustion technologies currently considered for power generation gas turbines to enable fuel flexibility, including the use of hydrogen and blends with natural gas. Some of these technologies have undergone significant development over the past decades with the main aims of improving gas turbine efficiency (e.g., by increasing firing temperatures) while simultaneously improving environmental performance (e.g., by reducing NOx emissions through improved fuel/air premixing). Others are in an early stage of development. These systems are generally categorized by the methods employed for fuel injection and fuel/air mixing in the gas turbine combustor. The main combustor types currently considered are given below, and the main report [1] considers each of them in more detail. It is possible for some of these systems to be used in combination.

Conventional or diffusion combustors

The main combustion technology in early generation gas turbines and is still the main technology used in aviation gas turbines. They are robust, stable and fuel flexible including being capable of burning high hydrogen fuels. However, they produce high levels of NOx unless diluent injection such as water or steam is used for NOx control often in combination with an exhaust NOx removal system such as Selective Catalytic Reduction (SCR). Diluent injection and exhaust cleaning are expensive and add complexity to the system. This is the main technology that manufacturers would offer today for 100% hydrogen combustion.

Lean premixed combustors

Lean premixed combustion became the main low NOx emissions combustion technologies for gas turbines from the late 1980s and is the dominant technology offered by manufacturers for natural gas combustion. This technology has low NOx when firing natural gas but can suffer from issues due to thermoacoustics, and when firing high reactivity fuels such as hydrogen can suffer from flashback damage. The extent to which current systems can accommodate hydrogen blends depends on the details of their design, but it is unlikely that current systems will be able to accommodate very high hydrogen concentrations without significant re-design.

Sequential combustion

This concept is used to optimize a combustion system and adjusts flame behaviour by having different fuel stages arranged axially (sequentially) along the flow path. Typically, the first stage is a lean premix combustor, but other concepts can be used. Sequential combustion may be used to reduce initial flame zone temperature to reduce NOx and can benefit turndown and fuel flexibility including enhanced hydrogen capability.

Micro-injection combustors

A number of concepts are being developed based on a multiplicity of small flames. This in principle could lead to low NOx due to the short residence time within these small flames. Both diffusion-based and premixed-based concepts are under development. The term "micromix" combustion is sometimes used to refer to both these concepts even though they are significantly different concepts. Mitsubishi have also developed a burner based on multiple small injectors, but in this case a single reaction zone is generated from a cluster of small injectors.

MILD combustion or Flameless oxidation

Another possible strategy to obtain low emissions and to handle reactive fuels is using highly diluted oxygen depleted oxidiser instead of air. Typically, the temperature of the reactants is high and the peak temperature in the flame zone and the temperature of the products is relatively modest. Modest temperatures and oxygen depletion lead to low NOx formation. This is referred to as Moderate or Intense Low oxygen Dilution (MILD) combustion. Usually, these conditions produce reaction zones that are less bright and distributed over larger areas than premixed flames. This reduces their visibility, hence the alternative name of flameless oxidation. Dilution and oxygen depletion of the oxidizer can be achieved in a number of ways including exhaust gas recirculation and humid air cycles.

Trapped vortex combustors

As the name suggests, a Trapped Vortex Combustor (TVC) utilises a vortex trapped within a cavity and several alternative arrangements are possible. Fuel is injected into the trapped vortex and mixing of recirculated combustion products and reactants occurs efficiently and rapidly. The recirculation of the hot gases generates combustion conditions typical of flameless oxidation resulting in low emissions, good fuel flexibility and low pressure drop.

2.4. Positive impacts and advantages of adding hydrogen

The main practical advantage of using hydrogen or a natural gas/hydrogen blend as a gas turbine fuel is the reduction in carbon dioxide emissions from the system at the point of use. Whether this has a net global benefit depends on the source of the hydrogen and whether any carbon dioxide has been emitted during the production and transmission of the hydrogen to the gas turbine. Even if zero carbon hydrogen is available the carbon emissions benefits are relatively modest unless a significant proportion of hydrogen is used in the blend. It can be seen from *Figure 5* that for a natural gas blend with 20vol% hydrogen content the reduction in CO_2 emissions would be less than 10%. To achieve 50% reduction in CO_2 emissions the blend must contain over 75vol% hydrogen. Thus, to achieve substantial reductions in carbon emissions in line with early goals of carbon reduction, blends with high hydrogen over 75% would be favoured.

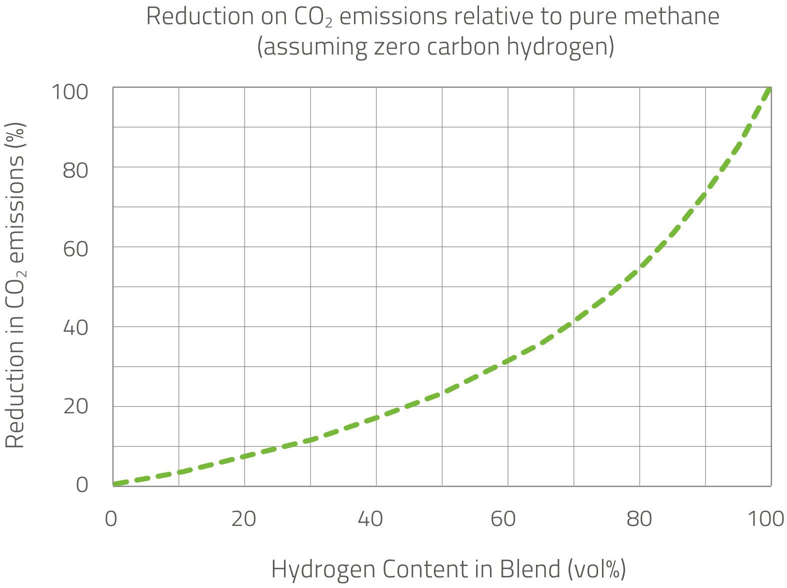

Figure 5. The impact of blending hydrogen with methane on CO_2 emissions
(Note: The trend is almost identical for blending hydrogen into typical natural gas)

In addition to the CO_2 reduction, in premixed systems, adding hydrogen reduces the equivalence ratio[1] at which lean blow out occurs. In real gas turbine applications, the lowest emissions compliant load is usually determined by the increase in CO emissions as fuel input is decreased to reduce load and the flame moves towards lean blow out. In principle adding hydrogen, even in modest amounts, will extend the emissions compliant turndown. A reduction in CO at part load has been seen in on-engine tests [11].

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[1] The equivalence ratio is the ratio of the actual fuel/air ratio in the fuel/air mixture to the stoichiometric fuel/air ratio. Stoichiometric combustions occurs when the air and fuel have the exact proportions so that all the oxygen in the air and all the fuel are consumed.

2.5. Adverse impacts of adding hydrogen

The main concerns relating to hydrogen combustion are NOx emissions, flashback and thermoacoustics and these have been discussed in Section 2.2. This section identifies three additional concerns

Impact on operation and component life

Hydrogen embrittlement in components upstream of the combustion zone needs careful consideration, but was not pursued in the main report [1] as it is not combustion related.

The different composition of the combustion products of hydrogen, especially the increase in water content, may affect both heat transfer and corrosion in the combustor, turbine and downstream components. This can lead to increased maintenance requirements or de-rating to compensate for the increased component damage.

Further research is needed to ensure that any risks are better understood and any de-rating can be kept to a minimum to minimise loss in output and efficiency.

Starting and shutdown

For some existing gas turbines operating on hydrogen-containing fuels an alternative starting fuel is required to reduce risks such as:

- Unwanted ignition in the exhaust or other downstream equipment after failed or faulty ignition or flame-out during shutdown, causing excessive pressure rise and damage to components downstream of the turbine
- Increased risk of "heavy" ignitions in the combustor due to delayed ignition, causing damage
- Flame stability, position and flashback issues during start/shutdown transients

The particular risks will depend on the gas turbine design, chosen combustion technology and start/shutdown procedures and will vary from gas turbine to gas turbine. However, the potential risks should be recognised.

Flame-out under normal operation

Exactly what will happen in the event of a flame failure depends strongly on the gas turbine design, combustion concept and control system, but controls are designed to prevent damage to equipment as far as practicable. In the event of a total flame failure, fuel will continue to be supplied until the failure is detected and the control system can react to the failure and shut off the fuel. Air will also continue to be supplied as the compressor will still be turning because of the inertia in the gas turbine rotor. Thus, in principle, a combustible fuel-air mixture could be supplied to components downstream of the flame zone. This mixture is then diluted by the addition of combustor and turbine cooling air. In typical natural gas fired gas turbines, this dilution usually results in a fuel/air mixture close to or below the lower flammability limit (LEL) and there is little risk of an unwanted ignition in the gas turbine exhaust or downstream equipment. However, addition of hydrogen to the fuel affects both the fuel concentration in the fuel/air mixture and the flammability limits of the mixture and increases the risk of generating a flammable mixture downstream of the turbine. A post turbine ignition in the exhaust can cause a significant and damaging pressure rise, thus this needs to be considered when evaluating the suitability of combustion control systems and procedures when increasing the hydrogen content in the fuel.

2.6. Modelling, validation, and testing

The main report [1] identifies challenges in the application of current modelling approaches to hydrogen and natural gas/hydrogen blends.

There have been significant recent advances in the chemical kinetics mechanisms available for detailed chemical kinetic calculations, but further development of improved mechanisms and their validation for hydrogen containing fuels at conditions representative of gas turbine combustion is needed. Improved and validated reduced mechanisms are needed to apply in higher order modelling like CFD to reduce calculation time and aid the development of combustors for high hydrogen fuels.

Computation Fluid Dynamics (CFD) using a Reynolds Averaged Navier Stokes (RANS) approach is one of the main combustion design tools. This approach depends on a knowledge of key transport and thermal properties of the fluids involved, usually represented by appropriate dimensionless groups, such as Schmidt, Turbulent Schmidt, Lewis and Prandlt numbers. The impact of hydrogen on these dimensionless groups needs to be taken into consideration. The understanding of these dimensionless groups and their application to RANS modelling for natural gas combustion have been optimised over decades and a significant amount of optimisation will be required to ensure that they can be used reliably for hydrogen containing fuels.

CFD using a Large Eddy Simulation (LES) approach requires fewer assumptions about the fluid properties, simulates detailed physics to a smaller scale and allows time varying analyses to be made, thus capture of periodic aerodynamic features (such as vortex formation and shedding) is possible where it is not with RANS. LES has demonstrated superior performance compared to RANS in many turbulent combustion applications, but it comes at the penalty of significantly longer computation times. Further development of LES models validated for hydrogen containing fuels together with improved academic access to supercomputing systems to reduce computational times will advance the development of combustion systems for hydrogen containing fuels.

The impact of hydrogen on thermoacoustics is an important factor to capture as soon as practicable during the design process as modifications and retrofits to mitigate problems can be prohibitively expensive. This produces particular challenges as unlike most combustion properties, rig testing cannot reliably indicate likely thermoacoustic behaviour and trends when operating in a gas turbine. To overcome this, thermoacoustic modelling is required. In principle, this can be achieved using detailed CFD using LES. However, this is usually too computationally demanding to be used for early-stage design studies, and the use of alternative approaches such as acoustic network modelling or the application of Helmholtz solvers together with measured or calculated flame acoustic response is needed. The impact of hydrogen on the flame response is not well understood and improved methods of measuring and calculating the flame response for hydrogen containing fuels is needed.

A large body of test cases exists for methane/natural gas combustion. These can be used to validate analytical models. This has been developed over decades, but a far more limited body of work exists for hydrogen combustion. This will reduce the confidence in the results obtained from mathematical models used in the development new hydrogen combustion applications because of the lack of adequate model validation. More test cases over a wider range of burner types, operating conditions and hydrogen contents are needed to ensure adequate validation of mathematical models to be used in the development of the future hydrogen combustion systems.

The development of robust combustion systems requires an appropriate combination of numerical and analytical modelling and practical testing. The transition to the combustion of hydrogen and hydrogen blends will only increase the need for such testing in addition to validation testing mentioned above. The testing required to facilitate this transition can be categorised as follows:

- Fundamental experimentation to develop an understanding of the underlying physics and chemistry of flames
- Testing to determine fundamental properties associated with flames
- Development testing of whole or partial combustion systems
- Full-scale/on-engine testing

Before newly developed or improved gas turbine combustion technologies for hydrogen containing fuels can be released for commercial application, full scale testing at engine realistic conditions is needed. This presents particular problems with the supply of sufficient quantities of hydrogen. This becomes more challenging for large power generation gas turbines. For example, full scale, on-engine testing of a 314MWe gas turbine at base load would require 24421kg/hr of hydrogen If supplied by hydrogen tube trailers with a capacity of 300kg, this would empty a trailer every 44 seconds. This is impractical and an alternative hydrogen supply would be needed for such full-scale testing. Even testing such a gas turbine with a 20vol% hydrogen blend would require a trailer every 11 minutes. Testing of smaller gas turbines on hydrogen blends is practicable, but availability of hydrogen and its transport to test sites is a significant consideration.

3. Conclusions and Recommendations

The main report [1] outlines a range of issues associated with the transition from natural gas as the primary fuel for land-based gas turbines to the use of hydrogen and hydrogen/natural gas blends and this report summarises this work. To facilitate the rapid introduction of hydrogen combustion in gas turbines and ensure that hydrogen fuels are treated on an equal basis to natural gas the following recommendations are made.

3.1. Emissions standards and legislation

When the mass production rate of NOx emissions is identical, reporting NOx emissions in mg/m^3 or ppmv on a dry basis corrected to 15% O_2 results in a significant disadvantage to hydrogen-containing fuels due to the different combustion products produced. This should be taken into account when assessing NOx emissions against emissions legislation and standards. To ensure equal treatment of hydrogen and hydrocarbon fuels, emissions standards should be set on a mass production basis per unit of fuel energy used or recognition should be given that when mg/m^3 or ppmv on a dry basis corrected to 15% O_2 is used, increased levels should be accepted to account for this difference. In order to encourage efficiency improvements, it may be appropriate to consider relaxations in requirements for higher efficiency configurations.

This study aimed to determine whether there was any fundamental reason why hydrogen should produce different levels of NOx to hydrocarbon fuels. Chemical kinetic calculations suggested that, for ideal flames, whether there is an increase or decrease in NOx will depend on flame temperature. At low temperatures, there could be a modest increase in NOx, (up to ~10%) when firing hydrogen, but at higher temperatures a small decrease in NOx may occur. Thus, there is no justification for a relaxation of emissions standards on the basis of best theoretically achievable results. However, in addition to its impact on fundamental chemical processes, hydrogen will have a profound impact on other relevant processes that impact NOx, such as mixing. Current natural gas combustors have had decades of optimisation and the differences that result from the introduction of hydrogen will mean substantial re-optimisation is required. Rig and on-engine test of existing lean premixed combustors show a substantial increase in NOX, even with modest hydrogen addition, confirming that substantial re-optimisation is required. Initially, it may be necessary to de-rate the gas turbine to achieve current emissions requirements, resulting in lower output and efficiency. During the transition to a high-hydrogen economy, it may be appropriate to consider some relaxation of NOx emissions levels to facilitate the transition and to ensure maximum use of low-carbon hydrogen with maximum reduction in carbon emissions.

3.2. Education and research

Hydrogen combustion will play an important part in the future of low carbon power generation and sufficient skills at first degree, postgraduate and postdoctoral levels will be needed. Combustion research depends on a number of inter-related disciplines and exploring all the inter dependencies is a significant research task. Appropriately targeted education and research activity at all levels including National and European, would facilitate the introduction of hydrogen for land-based gas turbines. Key areas of activity are seen to be:

1. Development of both taught- and research-based education in hydrogen combustion related technologies.

2. The development and validation of analytical tools such as chemical kinetic modelling, CFD, and acoustic modelling to reliably model combustion systems firing both hydrogen and hydrocarbon fuels will aid the rapid deployment of hydrogen technologies.
3. Fundamental studies (analytical, numerical and experimental) into key physical processes (such as mixing) and how they are affected by hydrogen addition.
4. Studies (analytical, numerical and experimental) into the improvement of existing low emissions combustion technologies to accommodate hydrogen.
5. The development of alternative hydrogen combustion technologies.
6. Studies into alternative cycles that facilitate low emissions hydrogen combustion.
7. The development of the understanding of the impact of hydrogen combustion products on combustor and turbine materials including the substrate metal and coatings such as oxidation resistant coatings, thermal barrier coatings and environmental protection coatings will ensure that minimum de-rating is needed to achieve adequate component life. This would ensure maximum gas turbine efficiency and maximum carbon reduction when firing hydrogen-containing fuels.
8. The development of improved additive manufacturing technologies for precision manufacture of complex burner components both for rapid prototyping and production purposes.
9. The development of control strategies to deal with the impact of changing fuel properties when operating on fuels with variable quantities of hydrogen will facilitate the operation on blended fuels and increase fuel flexibility for security of supply. This will also require the development of fast acting fuel hydrogen concentration sensors and flame sensors to support these control strategies.
10. Appropriate full-scale rig and engine development testing in addition to on-engine field trials and demonstration projects will ensure the timely introduction of hydrogen technologies with minimum disruption to power supplies. Early engine testing of new prototype hydrogen combustion systems is suited to equipment manufacturers and known/established 3rd party facilities where continued design and development can be performed quickly and under controlled conditions. Later stage pre-production combustion systems can then be field tested and demonstrated for longer term operation and durability with a higher level of success.

Appropriate encouragement and targeted support and funding for these areas would aid the smooth transition to future low carbon power generation.

3.3. Infrastructure development

There are different national strategies for the development of hydrogen production and supply systems both locally and internationally. For large scale power generation using hydrogen to be viable, large quantities of hydrogen must be economically available. In the transition from natural gas to pure hydrogen, hydrogen blending with natural gas may be used. Clarity regarding likely levels of blending on a national, regional and international level would aid the planning of the development of appropriate combustion technologies. Clear timescales for the introduction of particular levels of blending and ultimately 100% hydrogen would ensure the right level of research and development effort is allocated to meet them across the gas turbine value chain.

The generation of large amounts of affordable hydrogen for use in many industries is one aspect of the issue, another aspect is the transportation of hydrogen from generation sites or hubs to the end use locations. These end use facilities may need large amounts of hydrogen transported over small, medium and large distances. Clarity on the hydrogen transportation requirements would help determine research and development efforts for gas turbine compressor sets including the engine, package and hydrogen compressor.

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