HYDROGEN COMBUSTION WITHIN A GAS TURBINE REHEAT COMBUSTOR

Madhavan Poyyapakkam, John Wood, Steven Mayers, Andrea Ciani, Felix Guethe, Khawar Syed
Alstom
Baden, Switzerland

ABSTRACT
This paper describes a novel lean premixed reheat burner technology suitable for Hydrogen-rich fuels. The inlet temperature for such a combustor is very high and reaction of the fuel/oxidant mixture is initiated through auto-ignition, the delay time for which reduces significantly for Hydrogen-rich fuels in comparison to natural gases. Therefore the residence time available for premixing within the burner is reduced. The new reheat burner concept has been optimized to allow rapid fuel/oxidant mixing, to have a high flashback margin and to limit the pressure drop penalty.

The performance of the burner is described, initially in terms of its fluid dynamic properties and then its combustion characteristics. The latter are based upon full-scale high-pressure tests, where results are shown for two variants of the concept, one with a pressure drop comparable to today’s natural gas burners, and the other with a two-fold increase in pressure drop. Both burners indicated that Low NOx emissions, comparable to today’s natural gas burners, were feasible at reheating engine conditions (ca. 20 Bars and ca. 1000C inlet temperature). The higher pressure drop variant allowed a wider operating window. However the achievement of the lower pressure drop burner shows that the targeted Hydrogen-rich fuel (70/30 H₂/N₂ by volume) can be used within a reheat combustor without any penalty on gas turbine performance.

INTRODUCTION
Alstom is investigating the development of technologies for pre-combustion capture, where the Carbon is extracted upstream of the gas turbine, resulting in a Hydrogen-rich fuel. Such a fuel is very reactive and introduces significant challenges for lean premixed systems, as flashback within the burner can occur, which, if not leading to hardware damage, will result in high NOx emissions.

Research on lean premixed Hydrogen combustion for gas turbines has been reported on several occasions, e.g. [1]. The focus of the present paper however is lean premixed Hydrogen combustion within a reheat combustor, such as the SEV within Alstom’s GT24 and GT26 gas turbines [2]. In these machines, there are two combustors, a high pressure combustor (EV), located between the compressor and a high pressure turbine stage, and a reheat combustor (SEV) located between the high and low pressure turbines, as shown in Figure 1.

![Figure 1 - Cross-section of the GT24/GT26 engine displaying the relative combustor positions](image-url)
the fuel auto-ignites, and the auto-ignition delay time limits the
time for premixing the fuel and oxidant. The present reheat
burner concept has been developed for natural gas fuels to
operate in a dry low emissions mode, while water injection is
used to control NOx emissions in liquid-fuel operation.

The aim of the present work is to achieve low NOx
operation within a reheat combustor for Hydrogen-rich fuel,
without the need for additional dilution. The target fuel is 70%
Hydrogen and 30% Nitrogen (by volume), which was identified
within the European Union (EU) framework 6 project, ENCAP
[3], as a representative fuel for an IGCC-CCS plant which
achieves 90% carbon capture. This fuel composition has been
adopted as a target within the EU framework 7 project
DECARBit [4], which has co-funded the present work.

Sequential gas turbines are particularly suited for fuel
flexibility, which is demonstrated by the large range in Wobbe
index and variability in the content of higher (than CH
4
) Hydrocarbons that can be addressed. Part of this flexibility is
achieved through varying the loading of each combustor. For
example if the fuel is more reactive, the first combustor can
operate stably at a lower flame temperature. This in turn
reduces the inlet temperature to the reheat combustor, which
counteracts the fuel reactivity effect on the auto-ignition delay
time [5].

In the present case however, the target fuel is significantly
more reactive than natural gases, and the present SEV burner
concept needs to be adapted in order to achieve low NOx
emissions. A new concept has therefore been derived, the
performance of which is herein reported.

The next section describes the challenge faced with burning
Hydrogen within a reheat combustor. The critical parameter is
the auto-ignition delay time, which limits the time available for
premixing and is therefore a critical burner design parameter.
The auto-ignition delay time is explored by way of plug flow
reactor calculations. Subsequently, the implications of the
reduced auto-ignition delay time on the requirements of the new
concept are discussed. The concept is then assessed by
presenting the results of full-scale high-pressure tests and their
evaluation.

**NUMERICAL ANALYSIS OF AUTO-IGNITION DELAY TIMES**

Auto-ignition within a practical combustion system, such as
the SEV, is complex, as the auto-ignition process cannot be
separated from the fuel/oxidant mixing process. The pre-
ignition reactions that lead to the build-up of the key heat
release radicals, OH and O, are initiated as soon as fuel starts to
mix with the hot oxidant, and therefore heat and mass transport
play a significant role in their progress. However simple plug
flow reactor simulations are an effective method to identify the
major impact of different fuels and conditions, e.g. pressure and
initial temperature, on the magnitude of change in the auto-
ignition delay time.

In this section the auto-ignition delay time is investigated at
conditions representative of the SEV burner of a reheat gas
turbine. The analysis is conducted by way of idealised plug flow
reactors, utilising the Cantera package [6], where a homogenous
mixture of fuel and oxidant is set at an appropriate temperature
and pressure. The system is then integrated in time, under
adiabatic and constant pressure conditions. The GRI 3.0
mechanism [7] has been used.

The temperature through a typical plug flow computation is
illustrated in Figure 2. The ignition delay is defined, in common
with other studies (e.g. [8]), as the inflection point of
temperature for a plug flow reactor. This point represents the
maximum heat release during combustion since the inflection
point is the point where the first derivative of temperature with
time is at its highest and will not increase any further.

![Figure 2 – Typical temperature profile through a plug flow
computation. The vertical red line indicates the definition used
for the auto-ignition delay time.](image)

In the following, the effect of various parameters is
investigated with respect to their influence on the auto-ignition
delay time for a reference natural gas (97% CH
4
 and 3% C
2
H
6
) and Hydrogen-rich fuels.

The impact of temperature on the auto-ignition delay time
for natural gas and the target Hydrogen-rich fuel as a function
of fuel mole fraction is shown in Figure 3. For the higher
temperature, there is approximately an order of magnitude
reduction in auto-ignition delay time for the Hydrogen-rich fuel
in comparison to natural gas. The difference in auto-ignition
delay time for the two fuels can be much reduced by reducing
the initial temperature. The minimum ignition delay time for the
Hydrogen-rich case (labelled High H2) is at higher fuel mole
fraction when compared to the natural gas case.

![Figure 3 – Impact of temperature on the auto-ignition delay
time for natural gas and target Hydrogen-rich fuel. The red line
indicates the minimum ignition delay time for a reference natural
gas mixture and the target Hydrogen-rich fuel.](image)
A more detailed description of the dependence of the auto-ignition delay as a function of operating conditions is given in Figures 4 and 5, which show the effect of temperature and pressure for natural gas and pure hydrogen respectively.

Figure 4 shows a rather straightforward relationship for natural gas, in that the auto-ignition delay time reduces in a monotonic manner as pressure and temperature increase. Figure 5 shows a more complicated behaviour in the case of Hydrogen.

At low pressure and high inlet temperature, similar to the natural gas case, the auto-ignition delay time monotonically decreases as pressure and inlet temperature increase. However at lower temperatures the favoured chemical reaction pathway changes and the intermediate radical HO₂ becomes more important [9]. For higher pressures and low inlet temperatures, this causes the chemical behaviour to change and the auto-ignition delay time increases as pressure increases. This behaviour is such that at, for example, 1200K, the auto-ignition delay times at 1 bar and 20 bars are similar and are approximately 5 times longer than at 10 bars. When alternative mechanisms, for example that of Davis et al [10], are utilised the trend is similar to that given by the GRI3.0 mechanism, though the absolute values change.

In summary, the plug flow reactor analysis shows that, at 20 bar, the auto-ignition delay time for the Hydrogen-rich fuel is an order of magnitude shorter than that for natural gas (see Figure 3), and the temperature dependence of the auto-ignition delay time is approximately an order of magnitude greater for Hydrogen compared to natural gas (see Figures 4 & 5). The latter indicates that the inlet temperature can be used as an effective control mechanism for adjusting the auto-ignition delay time. A third significant finding from the present analysis is the complex pressure dependence of hydrogen auto-ignition. The trends obtained from plug flow reactor match with experimental results [9]. This shows that at low pressures the auto-ignition of hydrogen can be more challenging than at high pressures, depending upon the initial temperature. This is of great significance when one considers that the operating pressure within gas turbine combustors vary over engine load.

The results of the above analysis have been considered when establishing a lean premixed reheat burner concept for Hydrogen-rich fuel, as described in the next section.
REHEAT BURNER CONCEPT FOR HYDROGEN-RICH FUEL

Crucial to the design of the present SEV is the ability to well premix fuel and oxidizer within the auto-ignition delay times associated with natural gases, while utilizing a modest pressure drop. This is achieved through injecting fuel from a central lance in a direction normal to the main oxidant flow. Prior to fuel injection, 4 large vortex generators create a secondary flow system within the burner, into which the fuel is injected. The secondary flow structure is responsible for distributing the fuel and then mixing the fuel and oxidant at the molecular level through the resultant turbulent dissipation. The present concept is described in detail in, for example, [11].

The features of injecting fuel normal to the main flow (i.e. a jet-in-cross-flow configuration) and the large scale of the secondary flow pattern is excellent for achieving a high degree of premixing, but has limitations if the auto-ignition delay time is significantly reduced. The limit could be extended through increasing the velocity through the burner, which will in turn increase the rate of mixing between fuel and oxidant. This however has an increased pressure drop as a penalty, which becomes prohibitively high if the velocity needs to be increased to address an order of magnitude reduction in auto-ignition delay time. It is the limitation of the pressure drop penalty that has led to the development of a new reheat burner concept to address Hydrogen-rich fuels.

The present jet-in-cross-flow configuration is excellent for fuel distribution and mixing, however there is a wake region behind the jet, where residence times are relatively high. This can lead to auto-ignition in a region where the fuel and oxidant are not well mixed, and thus high NOx emissions. In the new concept therefore we have opted for “in-line” injection, where the fuel is injected in the flow direction. However the mixing of fuel jets in such a configuration has a critical drawback. The transverse spreading of the jets is relatively poor, and therefore a very large number of injection holes are required. This introduces practical issues as the fuelling system then introduces a large blockage in the flow path. Consequently, in-line injection has been combined with mixing elements, which serve to increase both the fuel distribution and the turbulent mixing. There is an optimization that can be reached between the number of fuel injectors and the size of the mixing devices in order to achieve fuel/oxidant mixing within a given residence time. For example, in the case of fewer fuel injectors, the mixing devices need to be larger, in order to achieve good transverse fuel distribution. The integral scale of the turbulence then becomes larger, which leads to a greater pressure drop required to achieve the required fine-scale mixing rate. As stated above, in the case of a larger number of fuel injectors, the fuelling system starts to introduce limitations. These considerations have led to the concept shown in Figure 6. The fuel is injected through a series of holes at the trailing edge of vanes placed in the main flow path. Given the high temperature of the main flow, the vanes are internally air cooled, with the bulk of the coolant ejected through the trailing edge of the vanes, and a small portion of it ejected through effusion holes. As in the current reheat burner concept, this cooling flow can be used to cool the flow in the neighbourhood of the fuel injectors to prolong the auto-ignition delay time. Vortex generators are positioned near the trailing edge of the vanes. These introduced a pattern of stream-wise vortices that serve to distribute the fuel and to drive the turbulent mixing process. These vortex generators are smaller than those in the present concept.

The fuel injector assembly for the new reheat burner concept is shown in Figure 6. This assembly is placed within a burner, whose profile may be chosen to further optimize the balance between auto-ignition delay time and pressure drop. For example, results of high-pressure combustion tests will be shown for two variants where the fuel injector is placed within burners of different cross sectional area and therefore different velocities. The high velocity burner has a smaller residence time and therefore should be capable of addressing more reactive circumstances, however at the expense of larger pressure drop.

Figure 6 – Fuel injector assembly for the new reheat burner concept for Hydrogen-rich fuel.

The performance of the new concept is examined in the next section, which presents results from CFD analyses (using the Fluent software) and testing which includes water analogy and combustion tests.
PERFORMANCE OF THE NEW REHEAT BURNER

In this section “In-line” configuration and “Baseline” configuration refer to the new reheat burner concept and the present SEV burner concept respectively.

As mentioned earlier, total pressure drop has been a key parameter that has influenced the selection of a burner suitable for Hydrogen-rich fuel. In Figure 7, the total pressure drop profile through the burner, for the new, In-line, and the present, Baseline, reheat burners are compared. These results are from non-reacting RANS-based CFD analyses, utilizing the Fluent code and the realizable k-epsilon turbulence model. Both simulations utilise the same mass flow, though the In-line configuration operates with a higher velocity, due to a narrower burner cross-section.

Figure 7 – Comparison of CFD results for the total pressure drop through the In-line and Baseline SEV burner concepts.

Both the baseline curve and the In-line curve show a region where there is a steep reduction in total pressure. In the Baseline case, the reduction begins sooner and has a larger overall magnitude. In both cases this reduction is due to the losses induced by the vortex generators. The In-line design results in a 35% reduction in overall total pressure drop. However, due to the higher velocities within this burner, there is a larger dump loss as the burner flow exits into the combustor. This is illustrated in Figure 8, which shows CFD results of the total pressure drop within the burner, without the dump loss, and the complete total pressure drop, including the dump loss.

Two sets of results are shown in Figure 8, termed “low Residence Time” and “High Residence Time” burners. Both utilise the same fuel injector assembly (In-line) however the burner within which it is placed differs. The high residence time burner has a larger cross sectional area and has been designed to give approximately the same overall pressure drop as the Baseline configuration. The Low Residence Time burner has a narrower cross section. This burner should allow successful operation under more reactive conditions, but as shown in Figure 8, at the expense of higher total pressure drop.

Figure 8 – CFD results of pressure drop for the burner only and for the burner and dump loss.

Despite the reduced pressure drop within the burner, indicated in Figure 7, the in-line system still achieves a high degree of fuel/oxidant mixing, as demonstrated in Figure 9. Here the assessment of mixing is demonstrated based on the results of water analogy testing, where full-scale models of the burners have been tested. In such testing water representing the main flow and the fuel are controlled separately, with the latter stream being doped with a dye. The dye fluoresces as a result of a laser sheet, which has been positioned at a number of different axial locations and is orientated normal to the flow direction. The image is captured with a camera that is positioned normal to the laser sheet. The mixing quality, defined as the ratio of the standard deviation to the mean of the fuel mass fraction, is determined through analysis of the light intensity pattern from a large number of images. The water analogy testing is described in detail elsewhere [12].

The mixing quality for the In-line configuration is initially poor in comparison to the Baseline case, Figure 9. This is due to the fuel in the Baseline cases being immediately distributed by the vortex generators, whereas for the In-line case, the secondary flow structures are smaller and are still in the process of establishing themselves, when the fuel is injected. Further downstream however, the Baseline and In-line results converge. Figure 9 also shows the dependence of the mixing quality upon momentum flux ratio. Although initially this leads to a variation in mixing quality, the difference very rapidly diminishes. The independence of the mixing quality to momentum flux ratio, is a valuable feature for allowing good operation over a range of fuel Wobbe index, and is therefore a beneficial feature for fuel flexibility.
The combustion performance of the new concept was evaluated by way of single burner high pressure testing, where the two variants already mentioned, both having the same fuel injector assembly but having burners of different cross sectional area, have been tested at full engine conditions. The experimental setup, which includes a pre-combustor and dilution system, for simulating the high-pressure turbine exit flow (in terms of temperature and oxygen content) is described in [13].

The target of the present work is to develop a lean premixed reheat burner technology that is suitable for Hydrogen-rich fuels. A key aim of this is to achieve low NOx emissions without the need for additional dilution, beyond the 30% volume of Nitrogen that the target fuel already contains. Focus below is therefore given to NOx emissions. The parameters varied have been the combustor inlet and exhaust temperature. The former influences the auto-ignition delay time, as shown in Figure 10.

The flame position and NOx emissions as a function of inlet temperature at a constant combustor exit temperature are illustrated in Figure 10. The flame position has been determined through monitoring the chemiluminescence emissions from the flame. Also shown are sample OH chemiluminescence images of the flame, for which the flow direction is from left to right. The zero location is at the plane of the burner exit, and higher values represent further downstream locations. It can be seen that below \( T_{IN}/T_{IN,REF}=1 \), the flame position, and the NOx emissions, are relatively independent of the inlet temperature. At higher temperatures however there is a rapid upstream shift in the flame, which is accompanied by an increase in NOx emissions. This boundary represents the limit of successful operation of the burner, even though the flame has not yet entered the burner. At lower inlet temperatures, though auto-ignition initiates the combustion, the location of the heat release zone is also strongly influenced by flame propagation that is anchored within the recirculation zones of the dump expansion. Operation within this regime is stable, as perturbation in parameters that influence the auto-ignition delay time, do not lead to strong perturbation in heat release. At higher inlet temperatures the flame location moves towards the burner exit, and the heat release zone is dominated by the auto-ignition process.

![Figure 9 - Mixing quality profile through the burner for the In-line and Baseline configurations. Z/H=0 is the fuel injection location. J is the fuel jet momentum flux ratio, J_1>J_2>J_3.](image9.png)

Figure 9 – Mixing quality profile through the burner for the In-line and Baseline configurations. Z/H=0 is the fuel injection location. J is the fuel jet momentum flux ratio, J_1>J_2>J_3.

![Figure 10 - Impact of Reheat burner inlet temperature on NOx emissions and flame position, from full-scale single burner high-pressure tests.](image10.png)

Figure 10 – Impact of Reheat burner inlet temperature on NOx emissions and flame position, from full-scale single burner high-pressure tests.

![Figure 11 - NOx emissions as a function of combustor inlet and exit temperature, for both the low and high residence time burners.](image11.png)

Figure 11 shows the NOx emissions as a function of combustor inlet and exit temperature, for both the low and high residence time burners. When converting the reheat burner NOx results to engine emissions it should be noted that the reheat combustor contributes to only part of the total emissions, i.e. a 2-fold increase of the NOx from the reheat burner, leads to a less than 2-fold increase in NOx emissions from the engine, and therefore the normalized NOx, shown in Figure 11, is not directly related to engine emissions. An engine NOx emission of 20ppm (at 15% O_2) corresponds to a normalised NOx value of 2.8 in Figure 11.
In the case of the low residence time burner, Figure 11 shows data for an inlet temperature, which is 7% lower than ISO base load conditions for the GT26. Under these conditions low NOx emissions can be achieved over a wide range of hot gas temperature. This burner however has approximately 2 times the pressure drop compared to the present natural gas burner, and would therefore have a detrimental effect on gas turbine efficiency. Data points are also plotted for the high residence time burner, which has been configured to have a pressure drop approximately the same as the present natural gas design. It can be seen that this too can achieve the same NOx characteristic as the low residence time burner, but at a slightly lower inlet temperature, - 8% reduction of ISO base load temperature. When the inlet temperature reduction is reduced to 5% for this burner, the NOx characteristic shows a notable increase. However all the data presented in Figure 11 show a sub 25ppm NOx (at 15% O\textsubscript{2}) capability, for a reheat gas turbine.

![Graph showing NOx emissions vs. T\textsubscript{HG}/T\textsubscript{HG,ref} for low and high residence time burners.](image)

**Figure 11** – NOx emissions obtained from full-scale single burner high-pressure tests. T\textsubscript{IN} and T\textsubscript{HG} are the SEV inlet and exit temperatures respectively.

**SUMMARY AND CONCLUSIONS**

A new reheat burner technology for highly reactive conditions has been presented. This technology is a result of a research project, which targets lean premixed combustion for Hydrogen-rich fuel, specifically 70/30 H\textsubscript{2}/N\textsubscript{2} by volume. A key characteristic that such a fuel presents is a much reduced auto-ignition delay time and therefore the time available for pre-mixing the fuel and oxidant is reduced.

The key features within the new burner technology are associated with the fuel injection system, where an optimization has been sought between pressure drop and fuel/oxidant mixing. Other factors influencing the design of the concept are the elimination of localized pockets of relatively long residence time within the pre-mixing zone, and the overall practicality of the design in terms of, for example, manufacturing and robustness.

The fuel injector comprises multi-point “in-line” fuel injection, coupled with mixing devices (vortex generators) that introduce stream-wise vortices that serve to distribute the fuel, as well as to introduce shear that drives the turbulent mixing process.

Single burner full-scale high-pressure combustion test results of the new burner concept have been presented. These show that, at reheat combustor conditions, premature auto-ignition within the burner can be avoided, allowing a high degree of premixing to be achieved, and thus also low NOx emissions. The emissions from the test rig translate into engine NOx emissions well below 25ppm (at 15% O\textsubscript{2}). Furthermore, these emission levels have been achieved with a burner having a pressure drop comparable with today’s natural gas reheat burner.

**NOMENCLATURE**

- \(dP\) Total pressure drop
- \(J\) Fuel momentum flux ratio
- \(NG\) Natural gas
- \(t\text{\textsubscript{ign}}\) Ignition delay times
- \(t\text{\textsubscript{ign,ref}}\) Reference ignition delay times
- \(T\text{\textsubscript{HG}}\) SEV hot gas temperature
- \(T\text{\textsubscript{HG,ref}}\) Reference SEV hot gas temperature
- \(T\text{\textsubscript{IN}}\) Ratio of SEV inlet temperature to Reference SEV inlet temperature
- \(T\text{\textsubscript{IN,SEV}}\) SEV inlet temperature
- \(T\text{\textsubscript{IN,SEV,ref}}\) Reference SEV inlet temperature
- \(Z/H\) Ratio of burner axial distance to burner height

**ACKNOWLEDGMENTS**

Alstom gratefully acknowledges the financial support of the European Union through the Framework 7 programme (project number 211971 - DECARBit). The authors would like to acknowledge their former colleague Anton Winkler, for his valued contribution to the present work.

**REFERENCES**

7. GRI3.0 Mechanism: http://www.me.berkeley.edu/gri_mech/