Gas turbines in a carbon-neutral society
10th International Gas Turbine Conference
11-15 October 2021

Paper ID Number: 15-IGTC21

HIGH HYDROGEN GAS TURBINE RETROFIT SOLUTION TO ELIMINATE CARBON EMISSIONS

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ABSTRACT

Gas turbines with the ability to operate on hydrogen offer a low carbon solution to support the stability of the energy grid. However, hydrogen is a highly reactive fuel and presents challenges for industry standard dry low NOx combustors to switch between natural gas and hydrogen fuel blends while remaining stable and with NOx emissions always below stringent limits. Significant concerns regarding emission compliance, combustion dynamics and stability must be addressed prior to operation on these fuels.

To address this, a consortium consisting of equipment manufacturers, academia and end-users was set-up. The key objective is to develop a gas turbine combustor retrofit solution for fuel flexible operation from 100% natural gas to 100% hydrogen, and any mixture thereof, suitable for gas turbines between 1-300 MW.

This paper presents the results from the first phase of the project, which focused on atmospheric testing of a combustor based on the FlameSheet™ technology and adapted to the 1.8 MW OP16 gas turbine. From the tests, it was found that it was possible to achieve 100% hydrogen combustion with single digit NOx emissions.

INTRODUCTION

The growth in renewable solar and wind energy has emphasized the need for flexibility to reliably balance the load on the energy grid with the ability to rapidly adjust output while using cost effective fuels, which also minimize carbon output. Gas turbines with the ability to operate on hydrogen offers a low carbon solution to support the stability of the energy grid. However, hydrogen is a highly reactive fuel and presents challenges for industry standard dry low NOx combustors to switch between natural gas and hydrogen fuel blends while remaining stable and with NOx emissions always below stringent limits. Significant concerns regarding emissions compliance, combustion dynamics and stability must be addressed prior to operation on these fuels.

To address this, a project consortium was set-up consisting of equipment manufacturers (Thomassen Energy, OPRA Turbines), academia (Delft University of Technology) and end-users (Vattenfall, Nobian, Emmtec Services). The major objective is to develop a gas turbine combustor retrofit solution for fuel flexible operation from 100% natural gas to 100% hydrogen and any mixture thereof, while maintaining sub 9 ppm NOx emissions. The solution will be applicable for gas turbines in a load range from 1 to 300 MW.

The engine proven FlameSheet™ lean premixed combustion system is the basis for the project development to achieve the extended capability. The project is split into 4 phases:

1. Atmospheric Test
2. High Pressure Test
3. Engine Demonstration
4. Commercial Operation

The present paper will discuss the work from Phase 1. This phase focuses on adapting the FlameSheet™ combustor to the OP16 gas turbine and execute tests in an atmospheric combustor rig. A key to successful combustion of hydrogen in low-emission combustors is to understand the boundary layer flash back phenomenon. In this phase the novel boundary layer flashback model developed by Delft University has been used to gain insight as well as to support the combustor development, and we will discuss this model and its results. The paper will be concluded with an outlook for the next phases of this program.

NOMENCLATURE

BLF	Boundary layer flashback
CFD	Computation fluid dynamics
GTOP	Gas turbine optimization package
HGP	Hot gas path
RANS	Reynolds-averaged Navier–Stokes

OP16 GAS TURBINE

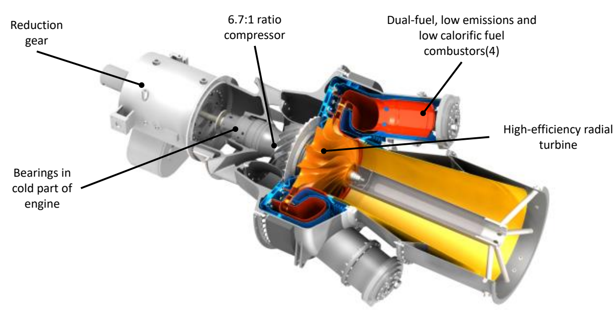

Figure 1. The OPRA OP16 gas turbine (courtesy of OPRA Turbines).

For Phase 1 of this program, the FlameSheet™ combustor has been optimized for the OP16 gas turbine. The OP16 (Figure 1) is a single-shaft all-radial gas turbine for industrial, commercial, marine and oil & gas applications. Since its market introduction more than 100 generator sets based on the OP16 gas turbine have been delivered worldwide. The OP16 gas turbine features a single stage centrifugal compressor with a nominal pressure ratio of 6.7:1. The moderate pressure ratio reduces the need for gas compression prior to introducing the fuel into the gas turbine. The radial turbine wheel, which is mounted back-to back with the compressor, has been aerodynamically optimized to achieve a high efficiency. The compact compressor/turbine configuration permits the use of an overhung rotor assembly where the bearings are located on the cold side only. The all-radial configuration makes the OP16 robust and insensitive to foreign object damages and fuel contaminants. The combustion system consists of four can combustors mounted in a reverse flow direction. This is convenient for the maintenance as well as to provide uniform temperature and flow distribution into the turbine.

The OP16 gas turbine rated at 1.85 MWe comes in a fully containerized solution that includes the OP16 gas turbine, fuel systems, generator, control system, air intake and ventilation system. The generator sets can be provided in a variety of configurations to meet specific customer requirements. These sets can be installed as single or multiple units, covering installation requirements from 1.5 to 10 MW.

FLAMESHEET™ COMBUSTOR TECHNOLOGY

The FlameSheet™ name is derived from the method used for injecting the fuel-air mixture as a continuous uninterrupted sheet into the reaction zone of the combustor whereupon an aerodynamically generated trapped vortex is utilized to anchor and stabilize the flame.

The combustor consists of two aerodynamic stages and four fuel stages. The stages are designed for specific operational aspects such as transient loading and extended turndown operation. The FlameSheet™ system is a combustor within a combustor. Each of these 2 combustors can be operated independently of each other. The two aerodynamic stages consist of a pilot along the axis of the combustor, and a main stage surrounding the pilot. The pilot and main stages are effectively two independent combustors with their own robust flame stabilization mechanisms. This allows either combustor to be operated with the other combustor OFF, which allows significant operational flexibility.

Figure illustrates the overall structure of the FlameSheet™ system. The pilot and main stages are fed from the compressor discharge plenum. Pilot air passes through the radially outermost circuit to the head end of the combustor where it enters a radial inflow swirler. Fuel is mixed into the air stream through a row of vanes. The fuel-air mixture then enters the combustor and a flame is swirl stabilized behind a bluff body on the centerline of the combustor. The main stage air flows along the backside of the combustion liner and then through a main fuel injector. The fuel-air mixture is then turned 180 degrees and flows into the combustor. As the flow enters the combustor it separates off the combustion liner and forms a strong recirculation region, or aerodynamically trapped vortex which stabilizes the flame.

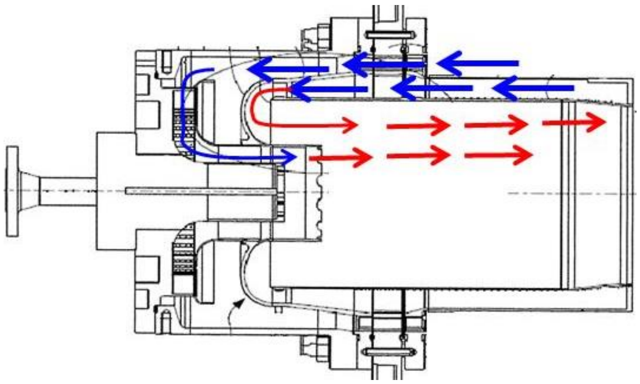

Figure 2. Overall flow design of FlameSheet™ system.

The fundamental design of the main stage flame stabilization mechanism may simply be described in comparison to a commonly used backward facing step system for flame stabilization. *Figure 3*illustrates this comparison. The aerodynamic point of flow separation is labelled as 'Equivalent Point 1.' Since the main stage flow enters the combustor in the opposite direction to the flow within the combustor, the flow separates at the end of the combustion liner. This separation creates a setting in which an aerodynamically trapped vortex anchors the flame and then recirculates hot combustion products providing enhanced stability, similar to the backward facing step scenario. However, the recirculation generated from the FlameSheet™ main stage is significantly stronger than a backward facing step due to the flow turning a full 180 degrees about 'Equivalent Point 1' in the FlameSheet™ system. Ultimately, the flow will reattach to the liner at 'Equivalent Point 2,' the exact position being dependent upon velocity magnitude and swirl magnitude within the combustor. Computational fluid dynamics (CFD) velocity and temperature contours are shown in *Figure 4*.

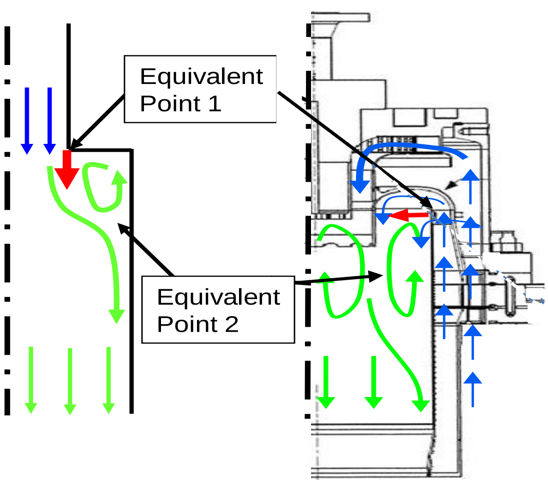

Figure 3. Illustration of flame stabilization mechanisms for a backward facing step and the FlameSheet™ combustor.

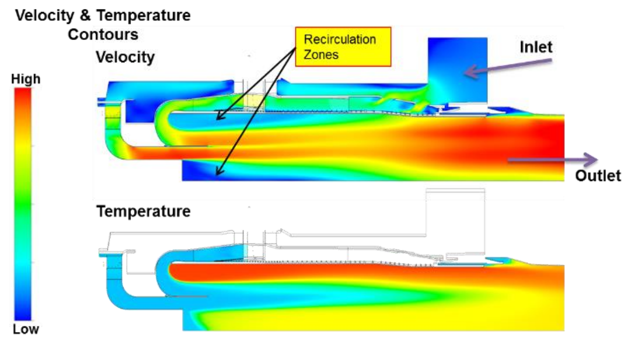

Figure 4. CFD Velocity contours(top) and Temperature Contours (bottom).

The design of the pilot stage flame stabilization mechanism is similar to that of a typical swirl stabilized flame. The center body recirculation region was designed for stability when the combustor is in pilot-only operation. In addition, the aerodynamic flow area and swirl were optimized through testing for optimum emissions performance at both the lower operating load and throughout premix load operation.

The pilot and main stages hence form two independent flame stabilization zones resulting in a "combustor within a combustor" configuration, which is key to enhancing operational flexibility.

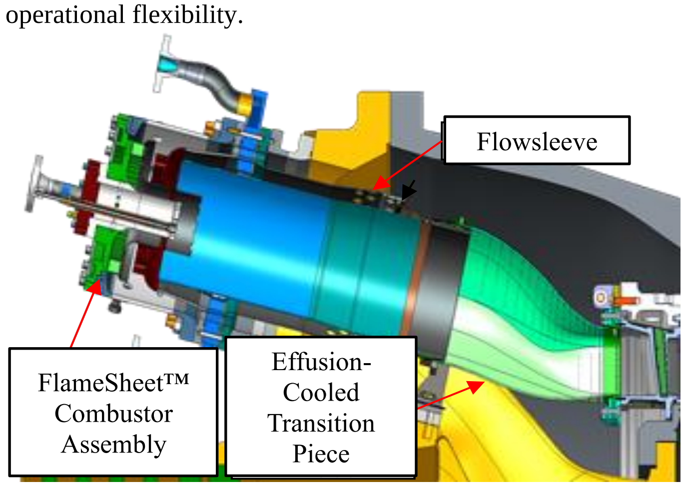

Figure 5.FlameSheet™ GTOP Combustion System.

In spring 2018 and spring 2019, four Low DP (low pressure-drop) FlameSheet™ systems (Figure 5) were installed on four Frame 7FA GE F-Class gas turbines (Rizkalla et al,2020). The FlameSheet™ installation was coupled with an advanced HGP Turbine Performance Upgrade for improved output and heat rate. *Figure 6* shows the installed combustors and transition pieces on one of the units.

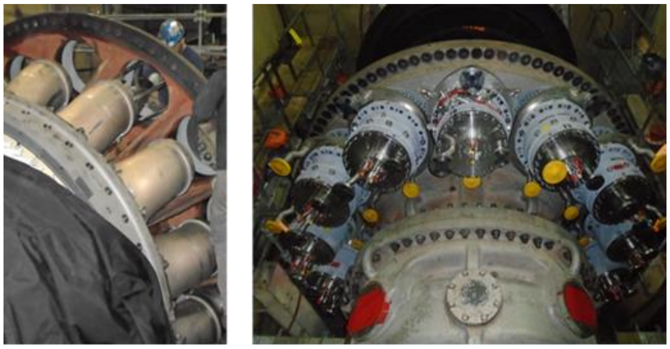

Figure 6. Low Pressure Drop FlameSheet™ Combustion System installed on a 7FA engine with effusion-cooled GTOP transition piece. (Rizkalla et al,2020)

Figure 7 shows a comparison of the NO_x and CO emissions between the FlameSheet™ Drop-in and FlameSheet™ Low DP configurations. At baseload and Peak operating points, it can be observed that the NO_x emissions for the Low DP configuration are now in-line with the Drop-in hardware and show a marked improvement from the previously reported value of 8.1 ppm. The new minimum NO_x value achieved was 4.7 ppm. The demonstrated sub-5 ppm level of NO_x in the combustion system is a remarkable achievement for an overfired gas turbine, especially considering an increase in reaction zone temperature of +30 K (+54°F) beyond the nominal F-Class baseload.

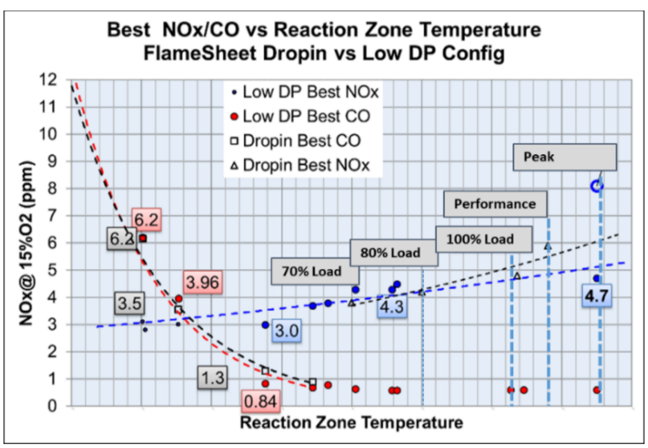

Figure 7. Best NOx / CO vs. Reaction Zone Temperature comparison for Low DP vs. Drop-in Configuration, with noted decrease in NOx after adjustment of fixed fuel split. (Rizkalla et al,2020)

BOUNDARY LAYER FLASHBACK MODEL

One of the most important issues in the application of hydrogen in gas turbine combustors, is the prevention of boundary layer flashback. Hydrogen flames are much more prone to flashback due to the following reasons:

- The (laminar) flame speed of hydrogen is 5-10 higher than the flame speed of natural gas.
- The high diffusivity of hydrogen leads to a low Lewis number at low equivalence ratio (typical for gas turbine combustor conditions). This leads to a further increase of the flame speed both due to flame stretch (negative Markstein length for low Lewis numbers) and unstable flame behavior.
- The quenching distance for hydrogen is much smaller than for natural gas.

Important for burner development is the availability of an engineering model to be able to calculate the potential risk on boundary layer flash back depending on the geometry and the local conditions (flow, temperature, composition).

Theory boundary layer flashback

Eichler (2011) was the first to show by experiments that boundary layer flashback in confined geometries, most relevant for flashback in gas turbine premixers**,** is caused by the influence of the flame backpressure on the incoming flow. In the classic theory, originally developed by Lewis and von Elbe **(**1943**)**, flashback occurs when the flow velocity in the boundary layer is smaller than the laminar flame speed, no influence of upstream pressure effect is included. The basic elements of the improved flame flash back theory for confined geometries from Eichler are:

- A (turbulent) flame can be present in the turbulent boundary layer at a wall distance larger than the quenching distance.
- The acceleration of the flow due to thermal expansion in the flame results in a backpressure.
- This (flame) backpressure can lead to flow reversal or even boundary layer instability allowing the flame to propagate upstream.
- As shown experimentally by Eichler (2011), Eichler et al. (2012) and numerically by Gruber et al. (2012), this upstream movement of the flame in the boundary layer occurs primarily in low velocity streaks by convex flame bulges.
- Gruber suggests, based on his calculations, that the formation of the backflow pockets, along with the subsequent mutual feedback mechanism, is due to the interaction of the approaching streaky turbulent flow pattern with the Darrieus–Landau hydrodynamic instability and pressure fluctuations triggered by the flame sheet.

TU Delft boundary layer flash back model

The TU Delft developed an engineering model for boundary layer flash back (BLF) based upon Eichler's observations and the BLF model developed by Hoferichter (2017). The basics of the TU Delft (Björnsson et al. 2020) model are:

- The model calculates the minimum back pressure generated by the flame required to achieve boundary layer instability. The boundary layer instability calculation is based upon a generalized version of the boundary layer stability criterion from Stratford (1959).
- The boundary layer velocity profile is derived from steady state (RANS) CFD simulations to enable applications to all geometries
- The adverse pressure gradient in Stratford's criterion is a combination of the mean flow adverse pressure gradient and the flame generated backpressure. The flame back pressure is calculated using the acceleration of the flow in the flame in combination with the turbulent flame speed. For the turbulent flame speed the Damköhler correlation between laminar flame speed and local turbulent conditions is used.
- A low Lewis number correction is implemented to correct the flame speed at low Le numbers.

The TU Delft engineering model can be used as a post processor for steady state RANS calculations.

Validation of the TU Delft model

The TU Delft BLF model has been validated against the experiments done by Eichler in a channel burner, tube burner and diffuser. The experiments have been executed at atmospheric pressure and 100% hydrogen.

An extensive validation is reported by Björnsson (2020). The most important results are shown below. In Figure ***8*** the TU Delft BLF model is compared with the results from the TU Munich BLF model (Hoferichter (2017)) and the experiments by Eichler (2011).

The main improvement of the TU Delft BLF model versus the TU Munich BLF model is the better performance at low equivalence ratio. This is due to the use of the low Lewis number correction instead of the Markstein length correction used by TU Munich. The low equivalence ratio and preheated conditions are very relevant for gas turbine applications.

The other case showing the capabilities of the TU Delft BLF model is the two degree diffuser. The model results are compared to experiments from Eichler (2011) at atmospheric conditions and 100% hydrogen.

Figure 9 shows the comparison between the experiments with a 0° channel, the 2° diffuser and 4 model results (a-d). The figure shows that at identical equivalence ratio, flashback occurs at a much lower equivalence ratio in a diffuser than in a straight channel flow.

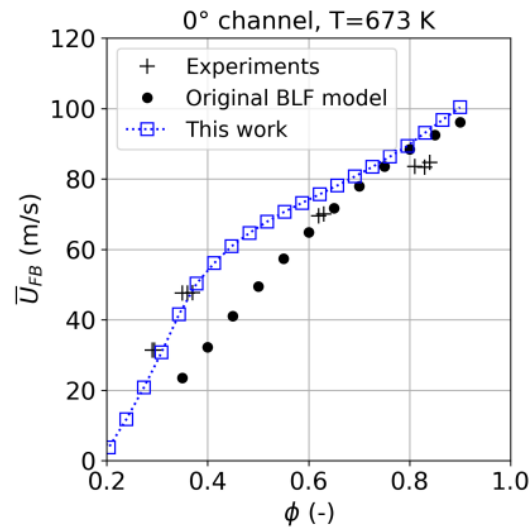

Figure 8. Validation of the TU Delft model against experiments from TU Munich. The UFB at the y-axis is the maximum velocity at which flash back occurs.

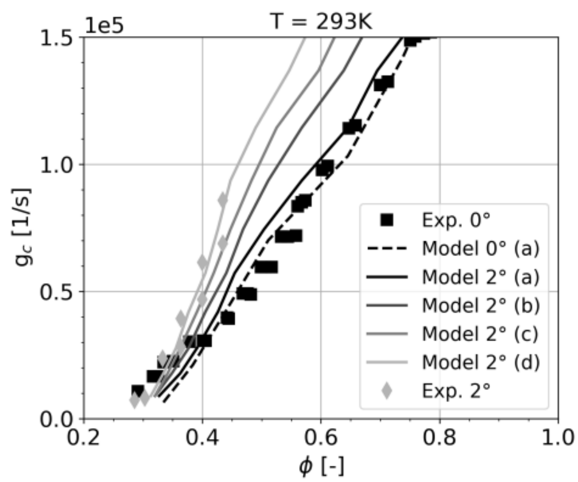

Figure 9. Predicted flashback limits in the 2 degree diffuser. The critical velocity gradient at which flashback occurs is plotted on the y-axis. The different models: (a) only fit of the boundary layer profile (b) + including the adverse pressure gradient from the main flow (c) + correction for u' from the experiments (d) + correction of C in the Damköhler turbulent flame speed from 1 to 1.1.

The model results show that this due to a combination of effects: the impact of the local boundary layer profile is limited (model 0° (a) versus model 2° (a)), an important contribution comes from the mean flow adverse pressure gradient (model 2° (b)). The RANS calculations underestimate the magnitude of the turbulent velocity fluctuations, this has been corrected in model 2° (c), model 2° (d) is a tuning of the constant *C* in the Damköhler turbulent flame speed equation.

The underestimation of the flashback limits by the TU Delft model is probably mainly because the turbulence is not well captured and that the impact of the low velocity streaks on the occurrence of flash back cannot be described well with this engineering model based upon RANS turbulence calculations.

Outlook

Results obtained from the FlameSheet^{TM} burner tests have been used for initial validation of the TU Delft boundary layer flashback model. The model was used to provide input for optimization of the modified combustor. The model will be developed further within this project and follow up projects. The main expected improvements are to be achieved by: better understanding of the role of low velocity turbulent streaks and the interaction between turbulence and flame backpressure, better understanding of the impact of the wall temperature and quenching distance and more insights into the low Lewis number effect on the flame speed. The model will be validated on the results

TEST SET-UP

The adapted FlameSheet^{TM} combustor has been tested using OPRA's atmospheric combustor test rig (**Error! Reference source not found.**). The main components of the test rig are the air fan, air preheater and the combustor. The air is taken from the surroundings by the fan and it is heated up to the same temperature as the combustor inlet temperature of the OPRA OP16 gas turbine. The pre-heated air is injected into the combustor module and the exhaust gases are emitted through an exhaust stack. The combustor inlet air mass flow can be varied between 0-0.35 kg/s and heated up to a temperature of 300 °C.

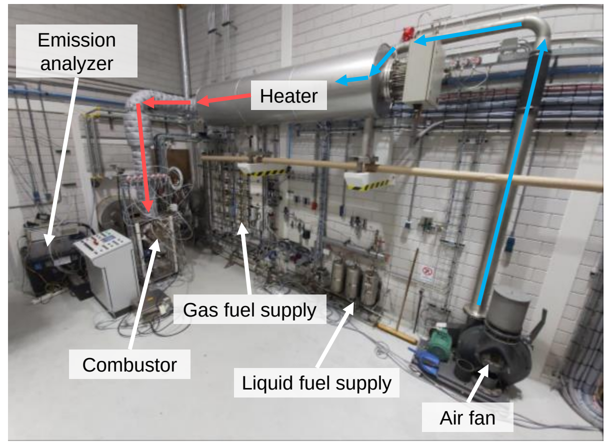

Figure 100. Overview of state-of-the-art atmospheric combustor test rig at OPRA.

The gaseous fuel is supplied by a gas mixing station, shown schematically in **Error! Reference source not found.**. The gas mixing station can supply gas mixtures consisting up to five different components. For this test campaign, hydrogen is supplied from gas cylinder bundles and Groningen type natural gas from the pipeline. A variety of pressure regulators, gas filters, safety relief valves, shutoff valves and vent valves ensure proper gas supply and safe operation of the system. The hydrogen and natural gas flow are continuously measured and controlled by mass flow controllers or flow meters combined with electrically actuated needle valves. A total of three gas mixtures is supplied to the combustor for the pilot, main 1 and main 2 fuel injectors. The control system of the test rig sets the flow of each individual component, thereby controlling the gas composition and fuel split to the different fuel injectors. The gas composition can be varied from 100% natural gas to 100% hydrogen and any mixture thereof.

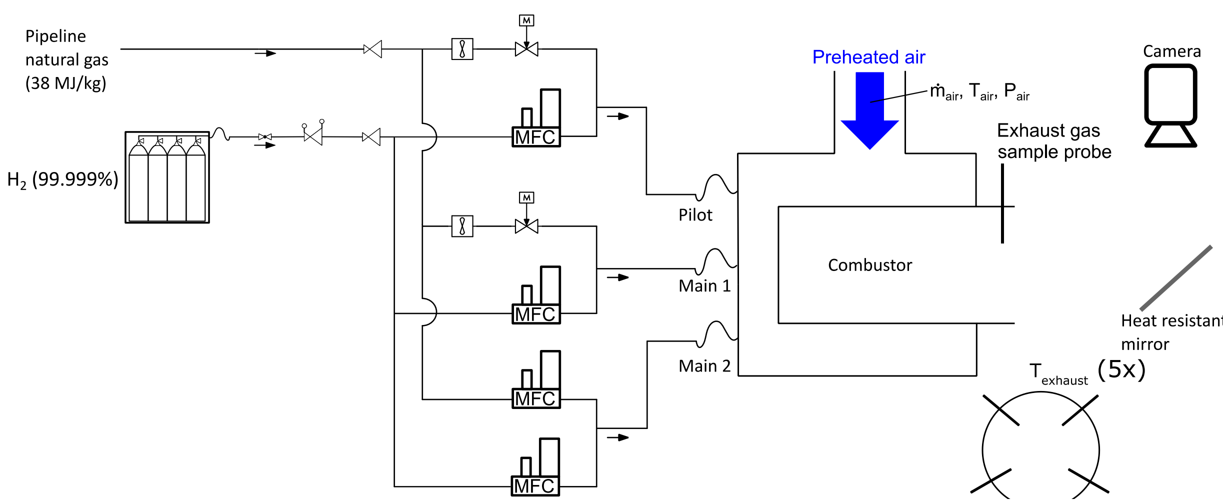

Figure 11. Schematic overview of the atmospheric combustor test rig equipped with a gas mixing station. Only parts relevant for this test campaign are shown. Main measurement locations are indicated.

The combustor inlet temperature, exhaust temperature and combustor air inlet pressure are measured continuously. The air mass flow is measured by dedicated equipment upstream of the air heater. The exhaust gas emissions are measured by an emission analyzer. The combustor is equipped with various pressure measurement locations to monitor the pressure drop over components. A series of thermocouples is installed to monitor metal and air temperatures at critical locations in the combustor. These thermocouples can also be used to detect flashback. The test rig is equipped with a camera, which looks via a heat resistant mirror in the exhaust to the outlet of the combustor. This camera is used to monitor the flame during operation.

TEST RESULTS

The OP16 FlameSheet^{TM} combustor is based on the original FlameSheet™ design, which was originally developed for large scale F-class machines. The result is a combustor that has a volume that is only a tenth of the original design. To assure similar performance and behavior a constant-velocity scaling approach has been utilized.

This scaling approach has been validated in-house in an extensive cold flow measurement campaign. Using a special flow fixture we were able to determine the effective flow areas of all the individual sections of the combustor. These numbers have confirmed that the scaled combustor meets the expected flow distribution. Furthermore, the measured flow area's have been used to build a robust model of the flow distribution in the combustor. Starting point in the atmospheric test campaign is validation of the performance of the baseline build. This build is fully based on a scaling of the original large-scale design and is used as a reference for the following optimized builds. The results show the fuel flexibility of the original design, without any modification on the fuel injectors, was already achieving 100% hydrogen at part load conditions.

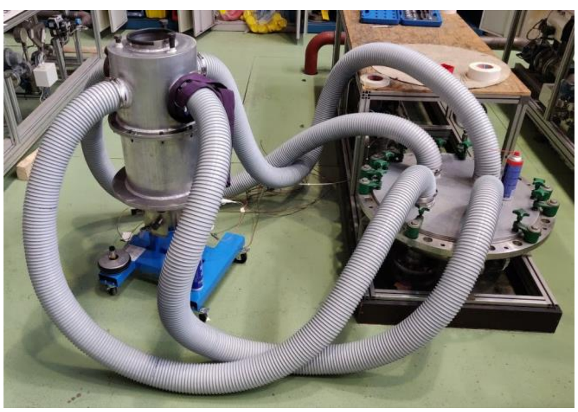

Figure 11.FlameSheet^{TM} combustor in the custom flow fixture at Thomassen Energy.

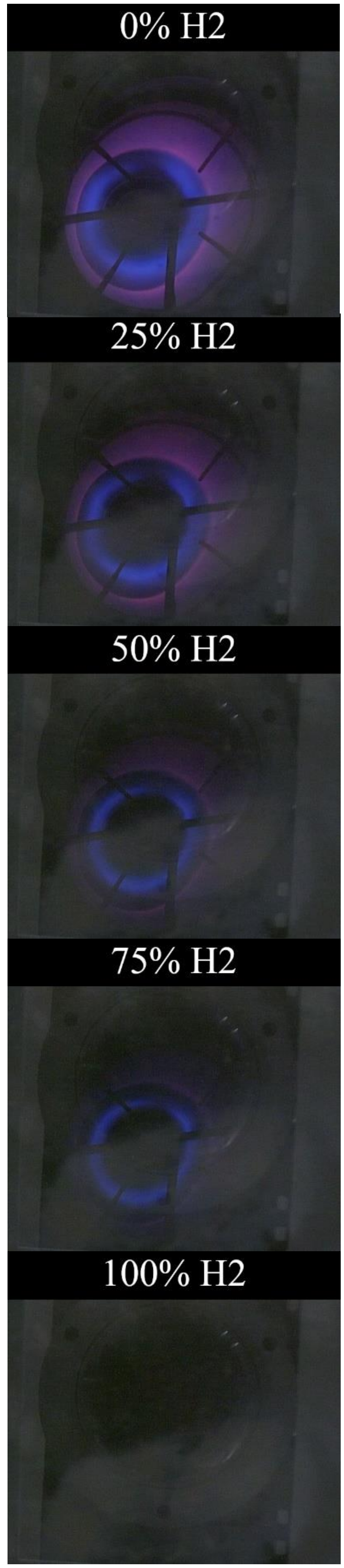

Figure 12. Visible light emissions at varying hydrogen content (vol%).

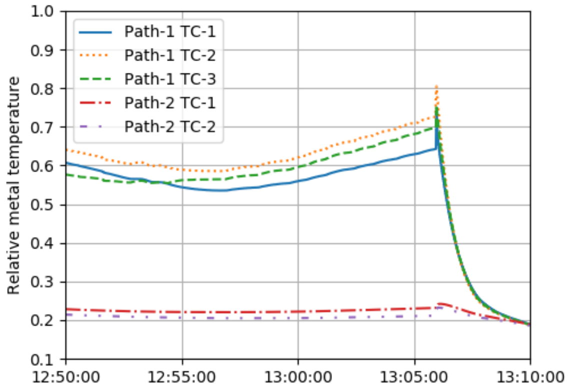

Figure 13. Typical metal thermocouple response during a flashback.

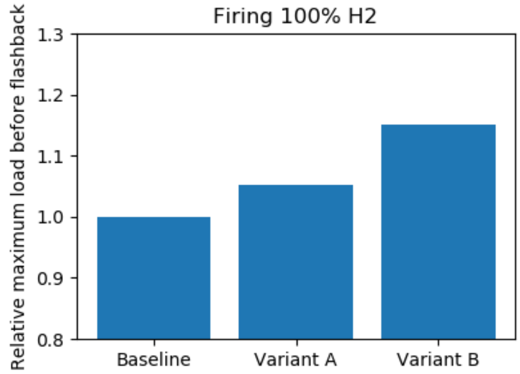

Figure 14. Increased flashback limits due to changed gas injection strategy.

At the indicated maximum load or maximum H_2 percentage a flashback occurs. Due to the limited emissions in the visible spectrum of hydrogen combustion (Figure 12) flashback is detected based on a sharp rise in temperature (**Error! Reference source not found.**). further validation of the TU Delft BLF model and was used in determining the optimization strategy for the combustor.

Due the high number of thermocouples installed not only the flashback itself is detected but also the pathway the flame front follows. This data was used to optimize the combustor several different components have been developed during the program:

- 2 different liners
- 3 different main gas injectors
- 2 different pilot injectors
- 2 different combustor head ends

More details of the atmospheric test campaign are discussed in (Bouten et al. 2021)

These variants are specifically developed to extend the flashback limits by optimizing the parameters also seen in the TU Delft BLF model focusing on increasing the local quenching distance in the boundary layer in combination with lowering the local fuel content.

First, gas injection strategies are explored resulting in 2 main variants on the baseline injector: Variant A uses a similar injection pattern as the baseline injector but is optimized to prevent boundary layer flashback and reduces flame stabilization areas. Variant B uses a completely novel fuel injector strategy which limits the risks of boundary layer flashback even further.

Both variants directly show improvement over the baseline injection (*Figure 14*). A noteworthy observation when testing variant B is that no flashback occurred at all. Load was only limited by the local cooling.

NOx emissions on natural gas for the three variants are all below 10 ppm and a large part is even below 5 ppm. Operation on hydrogen illustrated a path to sub-9 ppm NOx emissions and this is being validated in subsequent tests.

CONCLUSIONS

This paper has presented the outcome from the first phase in the High hydrogen gas turbine retrofit program. This first phase focused on atmospheric testing of a Flamesheet™ combustor for the OP16 gas turbine. The conclusion of this project is that we already succeeded in firing high loads when operating at 100% hydrogen by only changing the injection strategy. In combination with other parts and variants which are now being tested and the unique insights provided by the TU Delft BLF model it looks very promising to achieve the goal of a fuel flexible combustor able to fire 100% natural gas up to 100% hydrogen with sub 9 ppm NOx emissions.

Based on these results and the strong belief in the need for a low carbon support for grid stability the next phases are now in execution. The subsequent phase is focusing on combustor testing at engine representative pressure to further validate and optimize the performance before going over to real life OP16 engine tests. These pressure tests have been initiated in 2021. In the next phase, which is currently in preparation, the combustor technology will be applied to a large-scale industrial gas turbine enabling fuel flexible operation at an industrial site.

ACKNOWLEDGEMENTS

This work has been partly funded by Dutch hydrogen program within the Top Sector Energy area of the Dutch Ministry of Economic Affairs and Climate Policy.

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