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First *Last*

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DEMONSTRATION OF NATURAL GAS AND HYDROGEN CO-COMBUSTION IN AN INDUSTRIAL GAS TURBINE

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ABSTRACT

Hydrogen co-firing in a gas turbine is believed to cover an energy transition pathway with green hydrogen as a driver to lower the carbon footprint of existing thermal power generation or cogeneration plants through the gradual increase of hydrogen injection in the existing natural gas grid. Today there is limited operational experience on co-combustion of hydrogen and natural gas in an existing gas turbine in an industrial environment. The ENGIE owned Siemens SGT-600 (Alstom legacy GT10B) 24 MW industrial gas turbine in the port of Antwerp (Belgium) was selected as a demonstrator for co-firing natural gas with hydrogen as it enables ENGIE to perform tests at higher H_2 contents (up to 25 vol%) on a representative turbine with limited hydrogen volume flow (1 truck load at a time).

Several challenges like increasing risk of flame flashback due to the enhanced turbulent flame speed, avoiding higher NOx emissions due to an increase of local flame temperature, supply and homogeneous mixing of hydrogen with natural gas as well as safety aspects have to be addressed when dealing with hydrogen fuel blends.

In order to limit the risks of the industrial gas turbine testing a dual step approach was taken. ENGIE teamed up with the German Aerospace Center (DLR), Institute of Combustion Technology in Stuttgart to perform in a first step scaled-burner tests at gas turbine relevant operating conditions in their high-pressure combustor rig. In these tests the onset of flashback as well as the combustor characteristics with respect to burner wall temperatures, emissions and combustion dynamics were investigated for base load and part load conditions, both for pure natural gas and various natural gas and hydrogen blends. For H_2 < 30 vol% only minor effects on flame position and flame shape (analyzed based on OH chemiluminescence images) and NOx emission were found. For higher hydrogen contents the flame position moved upstream and a more compact shape was observed. For the investigated H_2 contents no flashback event was observed. However, thermo acoustics are strongly effected by hydrogen addition. In general, the scaled-burner tests were encouraging and enabled the second step, the exploration of hydrogen limits of the second generation DLE burner installed in the engine in Antwerp.*

To inject the hydrogen into the industrial gas turbine, a hydrogen supply line was developed and installed next to the gas turbine. All tests were performed on the existing gas turbine hardware without any modification. A test campaign of several operational tests at base and part load with hydrogen variation up to 25 vol% has been successfully performed where the gas composition, emissions, combustion dynamics and operational parameters are actively monitored in order to assess the impact of hydrogen on performance. Moreover, the impact of the hydrogen addition on the flame stability has been further assessed through the combustion tuning. The whole test campaign has been executed while the gas turbine stayed online, with no impact to the industrial steam customer. It has been proved that co-firing of up to 10% could be achieved with no adverse effects on the performance of the machine. Stable operation has been observed up to 25%vol hydrogen co-combustion, but with trespassing the local emission limits.

Keywords: hydrogen, natural gas, co-combustion, single burner tests, industrial gas turbine

1. INTRODUCTION AND MOTIVATION

One mayor challenge with respect to limit the effects on climate change is the de-carbonization of the power generation sector. Gas turbines (GT) can and will play an important role as a bridging technology from a fossil fuel dominated energy system towards a fully sustainable system with a lot of renewables (wind, sun, biomass) in the grid. Because of a fast ramp-up capacity und high load and fuel flexibility, gas turbines can compensate for highly intermittent power production from renewables. When fueling GT with carbon neutral fuels like hydrogen no negative climate effects will be present. Investigating the potential of existing GT in the field with respect to hydrogen tolerance or retrofitting GT with combustor hardware more suitable to burn hydrogen will definitely pave the way towards a hydrogen energy system. On the other hand, different chemical properties of hydrogen compared to natural gas (NG) poses significant combustor design challenges. Burning hydrogen is associated with a higher flame speed, higher flashback risk and a higher flame temperature. As a consequence, the flame will stabilize differently with a different flame shape and different dynamics. These different combustion physics affect combustor performance parameters such as hardware heat loading, ignition and blow-off, combustion instability limits, as well as pollutant formation.

Premixed H_2-enriched flame stability and emissions have been studied extensively in lab-scale model combustors [1-7]. Researchers observed that H_2 enrichment extends the operational window (extending lean blow-out limit), changes the extinction dynamics, and can also change the flame shape. Thermoacoustic oscillations in combustors occur when the combustor acoustics couple with heat release. High amplitudes of these oscillations can cause immediate damage or shorten hardware life time and are therefore highly undesirable. Emadi el al. [5] have been reporting that H_2 enrichment changes the combustion instability limits and dynamics by altering the heat release distribution and fluid dynamic properties.

The influence of hydrogen addition on turbulent and laminar flame speed has been investigated in [8]. The authors reported that up to a hydrogen content in the fuel of about 20 vol% only a moderate increase in turbulent flame speed is observed. For higher H_2 contents the turbulent flame speed rapidly increases nonlinearly towards much higher values.

Results of full-scale atmospheric pressure tests of industrial gas turbine burners are reported in [9, 10]. When adding hydrogen an increase in NO_x emissions due to chemical kinetics and locally higher temperatures was observed. The blowout limit was improved by H_2 addition and the flame dynamics were affected by the adding hydrogen. Flame chemiluminescence images showed that the flame size and shape are changed when the hydrogen content in the fuel is increased. The high reactivity and high flame speed associated with hydrogen causes the flame to be shorter and narrower. For hydrogen contents higher than 60 vol% the flame anchored inside the mixing tube.

Recent high-pressure test results of a constant pressure sequential combustion (CPSC) system reported in [11] show the feasibility to operate the standard combustion system with mixtures containing H_2 contents of up to approximately 70 vol%. However, this high hydrogen tolerance is due to the specific advantages of the CPSC System and cannot transferred to single stage combustor systems. For higher hydrogen concentrations derating of the combustor exit temperature has to be applied.

An overview of hydrogen burning capabilities of different commercial GT is given in [12], where new models can accept up to 60 vol% hydrogen with natural gas in premix combustion systems. The report indicates that up to 10 vol% mixing, no adaptations are required to the gas turbine, whereas starting from 10-30 vol% minor modifications might be needed. Current limits are largely based on tests in the lab, operational experience of full-engine or power plant tests is lacking. Therefore, the ability of existing gas turbines to burn larger shares of hydrogen is not well demonstrated yet.

The current investigation aims at to some extent filling this gap by proving the real limit of existing gas turbine hardware without modifications. In order to limit the risks of full engine testing with NG/H_2 blends a dual step approach was taken. As a first step, scaled-burner tests at GT relevant operating conditions with optical measurements were performed at DLR Stuttgart in which the onset of flashback as well as the combustor characteristics with respect to burner wall temperatures, emissions and combustion dynamics were investigated. These tests were performed for base load and part load conditions with natural gas and various natural gas and hydrogen blends. In general, the scaled-burner tests were encouraging and enabled the second step, the exploration of hydrogen limits of the second generation DLE burner installed in the gas turbine in Antwerp.

Although in the current study only a small contribution to the total thermal power is associated with the hydrogen added, see Figure 1 (in engine tests about 10 % for up to 25 vol% H_2 and about 22 % in single burner tests with up to 50 vol% H_2) these investigations may promote other applications and might serve as an enabler for a wider use of hydrogen blends in power generation.

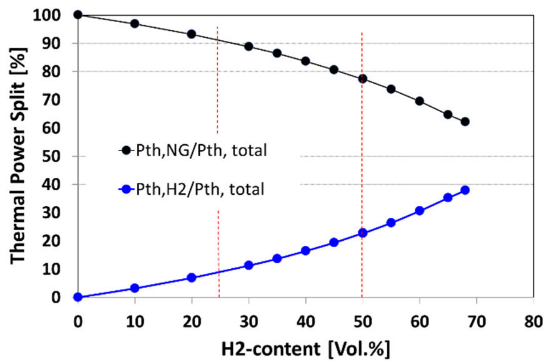


FIGURE 1: THERMAL POWER SPLIT OF NATURAL GAS / HYDROGEN BLENDS.

The current dual step approach provides a detailed data basis to assess the hydrogen tolerance of an existing GT operated in the field. To the authors knowledge, it is the first time burning H_2/NG blends up to 25 vol% has been demonstrated in a full GT power plant operation without hardware changes to the lean premixed combustor.

2. MATERIALS AND METHODS

2.1 Experimental Set-up of Single Burner Tests

HBK-S test rig: The single burner combustion tests were performed in the high-pressure combustor rig at DLR Stuttgart (HBK-S). The rig is capable to test geometrically-scaled burners and combustors at gas turbine relevant operating conditions and offers extremely good optical access to the test section thus allowing detailed investigations of combustion phenomena thanks to the application of optical and laser diagnostics. A more detailed description can be found in [13, 14].

Burner and combustor: A geometrically downscaled version of a gas turbine burner (Alstom EV burner) [15, 16] combined with a DLR designed pilot lance was integrated in an optical accessible combustor with a hexagonal cross-section shown in Figure 2. The basic design feature of this swirl-stabilized burner are two cone halves, shifted radially apart from each other to form two tangential air inlet slots. With this concept, a tangential velocity component is induced in the flow with an increasing swirl strength downstream resulting in a vortex break down close to the burner exit. The fuel is injected through small holes along the tangential air inlet slots in a jet in cross-flow arrangement and mixes with the entering combustion air. Additional fuel can be axially injected through two jets at the tip of a central pilot lance. The two fuel flows (tangential air inlet slots and pilot lance) can be controlled separately to allow different fuel staging conditions. The staging ratio is defined as the ratio of the fuel mass flow rate through the pilot lance to the total fuel mass flow rate. The burner front plate was air-cooled by effusion cooling.

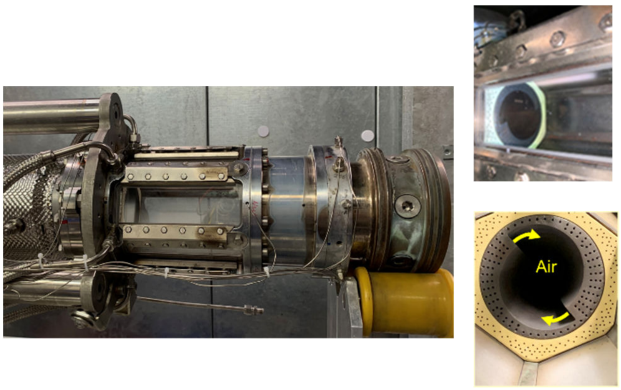


FIGURE 2: BURNER, COMBUSTOR HARDWARE USED IN THE SINGLE BURNER TESTS AT DLR.

The scaled-burner had similar features as the burners in the engine combustor with respect to pilot lance, burner and combustor geometry, e.g. cone angle and expansion ratio. The burner walls were instrumented with K-type thermocouples to measure material temperatures at certain burner wall locations.

Operating conditions and measurement techniques: The combustor was operated with NG/H_2 blends containing of up to 50 vol% hydrogen at base load and up to 25 vol% at part load conditions (see Table 1 for details) resulting in a total thermal power of 975 kW and 783 kW, respectively.

	P [bar]	T air [°C]	Staging [%]	H2 content [Vol.%]	Phi (global)	thermal Power [kW]	T adiabatic [°C]
Base load	13.7	381	88 / 12	0 - 50	0.546 - 0.525	975	1570
Part load	11.2	335	84 / 16	0 - 25	0.50 - 0.494	783	1451

TABLE 1: OPERATING CONDITIONS OF SINGLE BURNER TESTS DERIVED FROM ENGINE OPERATING CONDITIONS

The runs at each load condition were performed at different hydrogen contents by ramping-up the hydrogen contents in steps of 5 (10) vol% keeping the staging ratio and the flame temperature constant. For base load and part load conditions up to a hydrogen content of 15, respectively 20 vol%, the hydrogen is added only in the main fuel line. For higher H_2 amounts both fuel lines, pilot and main, were doped with the same hydrogen content. In order to keep the flame temperature (turbine inlet temperature in the engine) constant, the equivalence ratio was adapted to account for a higher adiabatic flame temperature due to hydrogen addition.

The NO_x (NO, NO_2) and CO emissions together with the main exhaust gas concentrations like O_2 and CO_2 were measured with a classical exhaust gas analysis system and a suction probe located approx. 74 mm downstream of the combustion chamber exit. The NO and NO_2 concentrations were determined by means of UV absorption (ABB Limas 11), the CO and CO_2 concentrations by IR absorption (ABB URAS 26), and the O_2 concentration by paramagnetism (ABB Magnos 206) at dry conditions. All concentrations of NO_x and CO were normalized to 15% O_2. The measured data recorded every 5 s were averaged for the time interval (>2 min) of stable operating conditions.

Dynamic pressure pulsations are measured at the combustor exit along the converging nozzle with piezoelectric pressure transducers (Kistler 4045A50) and evaluated by fast Fourier transformation once per second. Steel tubes with a length of about 2 m and an inner diameter of 4 mm are used to connect the pressure tab with the pressure transducer. At the end of the tubing absolute pressure transducers with a measuring range of 0–50 bar are mounted. The signals are amplified and recorded at a sampling rate of 20 kHz.

OH* Chemiluminescence (CL) measurements: In order to gain information on the flame shape and position the OH* chemiluminescence (OH*-CL) signal was recorded. OH radicals in the electronically excited state (OH*) are formed by chemical reactions in the reaction zone, predominantly in hydrocarbon flames via the reaction CH + O2 ←→ CO + OH* [17]. The chemiluminescence emission of OH* is a spontaneous emission and can be imaged directly with a camera, usually equipped with an image intensifier and an appropriate filter. OH* is only formed within the flame front and has a short lifetime. Thus, OH*-CL provides a good qualitative indication of the position and shape of the heat release zone. The CL signal was imaged from the top and side using two sCMOS camera (LaVision Imager sCMOS) equipped with external image intensifier (LaVision IRO). The intensifier/camera systems were equipped with a Halle UV quartz glass objective (focal length f = 64 mm; side view) or a Nikkor UV quartz glass objective (focal length f = 105 mm; top view) in combination with interference filters (resulting in a transmission window at 310 ± 15 nm). The resulting field of view were 105 x 175 mm (top view) and 56 ×

175 mm (side view) with a spatial resolution of 0.16 mm. For each operating condition 500 single instantaneous images were recorded with a frame rate of 40 Hz with two cameras.

The flame penetration was determined based on the OH* chemiluminescence intensities to identify the leading and trailing flame edge using a 10 % of the maximum threshold of the average images. A sensitivity analysis was conducted varying the threshold from 50 – 150% compared to the reference value (i.e. corresponding 5 – 15 % of the maximum). The effect of the arguably strong threshold variation is approximately 10 % and thus comparatively modest. More importantly, all trends are maintained.

2.2 Set-up of industrial gas turbine tests

The Siemens SGT-600 2nd generation industrial gas turbine is selected for the hydrogen co-combustion tests. The power output is rated at 24 MW, general operating conditions are given in Table 1. This industrial gas turbine is integrated in one of the co-generation sites of ENGIE in the port of Antwerp, Belgium.

A hydrogen gas expansion station was developed and manufactured to mix a supply of hydrogen with natural gas before being injected in the gas turbine. Figure 3 shows an overview of the installation. This set-up allowed to connect a hydrogen truck trailer to perform the co-combustion tests.

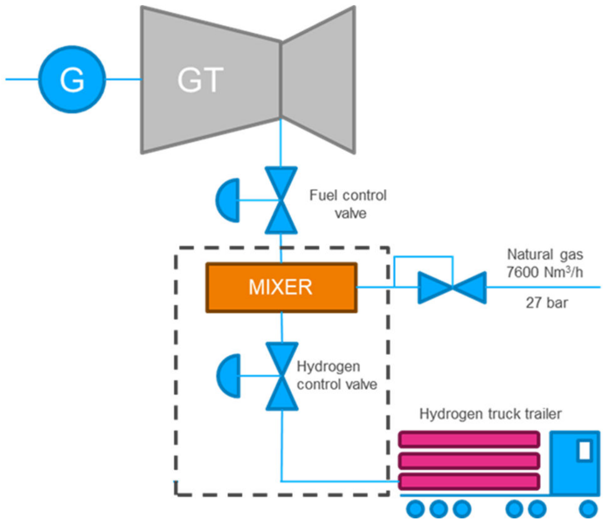


FIGURE 3: SCHEMATIC VIEW OF THE INSTALLATION

The expansion station consists of the following elements:

- Hydrogen unloading station; a hydrogen tube trailer was connected to the unloading station to supply the hydrogen
- Hydrogen pressure reducing line
- A 3D additive manufactured flow controller
- Mixing station of natural gas and hydrogen

The functional requirements were:

- The piping system should be able to accommodate the maximum flow (2200 Nm³/hour) at 200 bar.
- The high-pressure hydrogen should be expanded to match the natural gas pressure (≈27 bar).
- A controlled vol% shall be mixed with the existing natural gas line before injection into the gas turbine combustion system.
- Hydrogen and natural gas shall be mixed homogeneously before injected into the GT.
- The hydrogen content shall be controlled at an accuracy of ± 0.5 vol%.
- The fuel injection system shall accommodate a hydrogen flow between 100 and 2200 Nm³/h.
- In case of an emergency stop of the gas turbine, all valves should go into a failsafe position. This command will be hard wired from the main control system. Moreover, a heartbeat will be exchanged over the communication protocol, prohibiting the injection of hydrogen in case of loss of communication.
- The system should include all connections of nitrogen purging, hydrogen venting, etc.

The injection installation has been commissioned in March 2021, tests have been performed in March and April 2021, with a total of 9 truckloads of hydrogen of 250 kg each.

3. RESULTS

3.1 Single Burner Tests

Tests at base and part load conditions (see Table 1) were performed at various hydrogen contents up to 50 vol% to evaluate the flashback risk and to investigate the effects of hydrogen addition on flame position (heat release), material temperatures as well as thermo acoustics and emissions. At the investigated operating conditions and H_2 contents no flashback event is observed.

Flame position, flame shape and flame penetration: In Figure 4 and 5 results of the OH*-CL measurements at base load conditions are presented. In figure 4 averaged images (left column, labelled with “avg”) and root-mean-square results (labelled with “rms”) are shown for the top view (x-z direction). In addition, averaged images from the side view (x-y direction) are plotted. A red dashed line is added in the plot in order to better illustrated the maximum axial extension of the averaged flames.

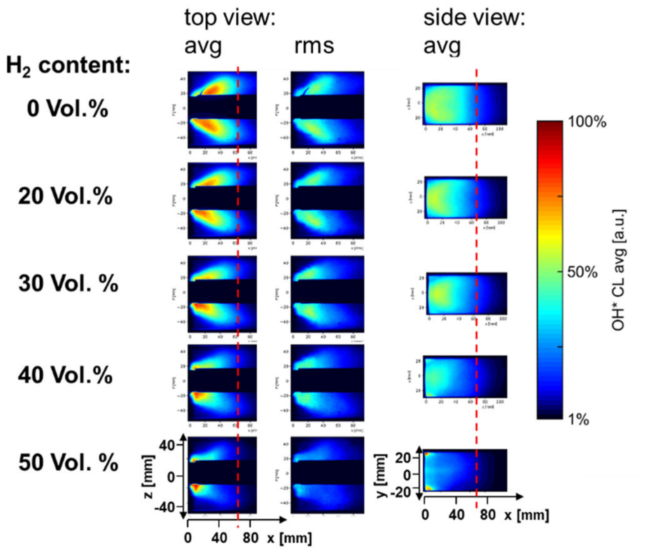


FIGURE 4: OH*-CL FLAME IMAGES AT BASE LOAD CONDITIONS FOR DIFFERENT HYDROGEN LEVELS.

The results of the averaged images show that the flame position and shape of the heat release zone are only moderately affected by hydrogen addition up to values of 20 vol% H_2. For higher hydrogen contents (H_2 > 20 Vol.%) the flame is getting significantly shorter and OH*-CL signal intensity increases. For even higher H_2 contents (H_2 > 40 Vol.%) the flame is anchoring inside the burner cone. The reason for the upstream movement of the flame position and the higher OH*-CL intensities at higher H_2 contents can be attributed to a higher turbulent flame speed [8] and a significantly higher reactivity of a NG/H_2 mixture with 50 vol% H_2 compared to blends with only 20 vol% H_2 or a pure natural gas flame. With an increasing hydrogen content the spatial and temporal OH*-CL signal intensity fluctuations decrease indicating lower flame position fluctuations. This can be attributed to the well-known flame stabilizing effects associated with adding hydrogen.

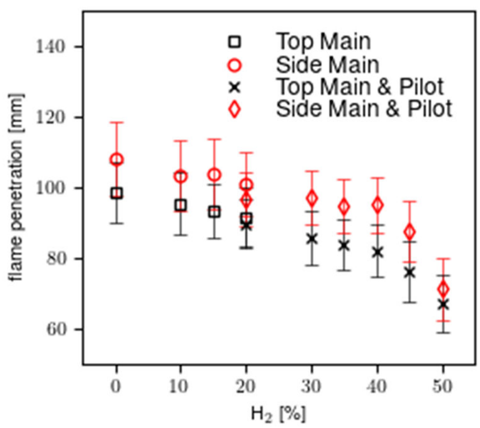


FIGURE 5: INFLUENCE OF HYDROGEN ON FLAME POSITION AND PENETRATION LENGTH AT BASE LOAD CONDITIONS.

Figure 5 illustrates the effect of hydrogen addition on the flame penetration. The symbols represent the mean values, the "bars" illustrate the sensitivity of the penetration length to the selected threshold in the data analysis (see description OH*-CL analysis). For moderate H_2 values (< 20 vol%) the flame penetration length does only slightly decrease (≈10 % reduction), whereas for higher H_2 contents (> 30 vol%) the influence is getting stronger resulting in a 65% flame penetration length reduction at 50 vol% hydrogen added. Again, these results can be explained by significantly higher flame speed values of the NG/H_2 blends containing higher amounts of hydrogen.

The averaged results of the flame position, shape, and penetration at part load condition are presented in Figures 6 and 7. The images are shown in a similar way than the ones in Figures 4 and 5. In the runs at part load condition hydrogen was added in two different ways. First, adding hydrogen only to the main fuel line (e.g. for 10 and 15 vol% H_2, labelled "main") and secondly doping both fuel lines (pilot lance and main) with hydrogen (labelled "pilot & main"). For both variations, only minor effects are observed with respect to the position and shape of the flame and the heat release zone and the flame penetration is also only moderately reduced (by about 10%). The results also document that doping the main fuel line only or adding hydrogen to both fuel lines, pilot and main, doesn't make a difference. The effect of hydrogen addition in the range of up to 25 vol% is relatively weak and can be again explained with the only moderate increase of the turbulent flame speed in this H_2 content range.

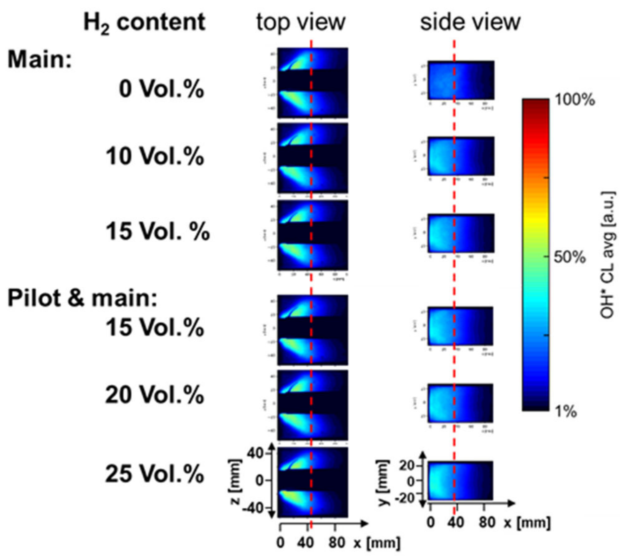


FIGURE 6: OH*-CL FLAME IMAGES AT PART LOAD CONDITIONS FOR DIFFERENT HYDROGEN LEVELS.

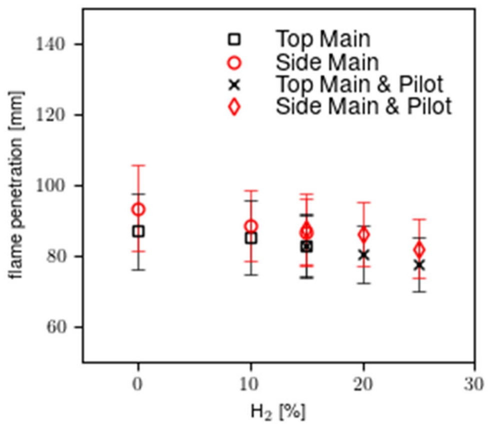
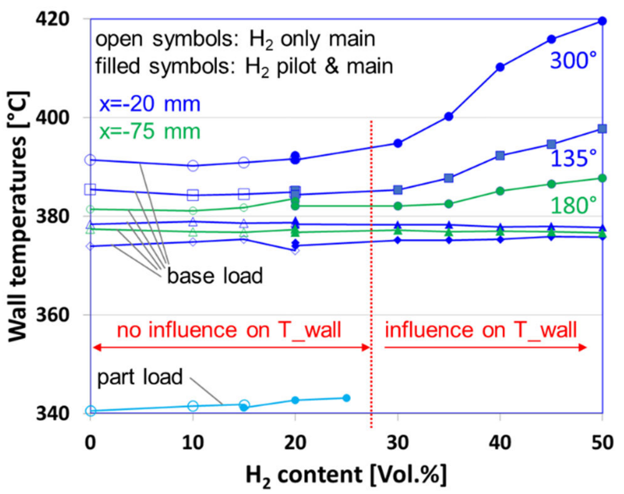
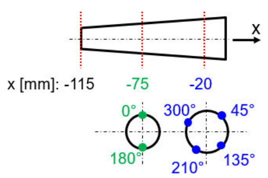


FIGURE 7: INFLUENCE OF HYDROGEN ON AVERAGED FLAME POSITION AND PENETRATION LENGTH AT PART LOAD CONDITION.

Wall temperature: Because of a nearly unchanged flame position at hydrogen contents lower than 25 vol% no influence on wall temperature is observed at base and part load conditions (see Figure 8). For higher hydrogen contents some thermocouple. e.g. at an axial position of –20 mm and circumferential positions of 135° and 300°, and x = –75mm and 180°, show an increase in wall temperature. At 50 vol% hydrogen content this increase was about 30 °C which is not critical.





Sketch of the thermocouple locations and orientation at the burner wall (0° = top, 180°= bottom).

FIGURE 8: INFLUENCE OF HYDROGEN ADDITION ON BURNER WALL TEMPERATURES.

Thermo acoustics: At base and part load conditions and the full range of hydrogen content variation no high-frequency pulsations above 1 kHz are observed. The corresponding results of the pressure pulsation measurements are presented in Figures 9 and 10. Plotted are the mean spectra which represent a Fast Fourier Transformation (FFT) of 50 individual pulsation measurements and the peak spectra, representing the spectrum with the highest amplitude. For base load condition and all measured H_2 contents the frequencies with the highest peak spectrum are in the range of 430 to 500 Hz with one exception, the measurement at 40 Vol. H_2 which shows a much lower frequency (see Figure 9). No reason can be given for this, for a detailed analysis more individual spectra would be needed but this is not in the focus of the present study. At base load condition a shift in the acoustic frequency is observed with H_2 addition. The frequency is shifted from 454 Hz for pure NG to 496 Hz at 50 Vol.% H_2. The reason is the change of flame position and heat release zone which results in a different acoustic frequency. In addition, the pressure amplitudes decrease with H_2 content. No differences in the acoustic frequencies are found between H_2 addition only in the main fuel line of doping both, the pilot and main fuel lines. This can be attributed to the same position of the flame and heat release zone which do not affect the acoustics.

The results at part load conditions are presented in Figure 10. With adding hydrogen, a moderate shift of the acoustic frequencies from 431 Hz for NG to 457 Hz at 25 Vol. % H_2 is observed. At the same time the pressure amplitudes increase with a higher H_2 content. Slightly higher frequencies and amplitudes are measured in case of a H_2 addition in the main fuel line only.

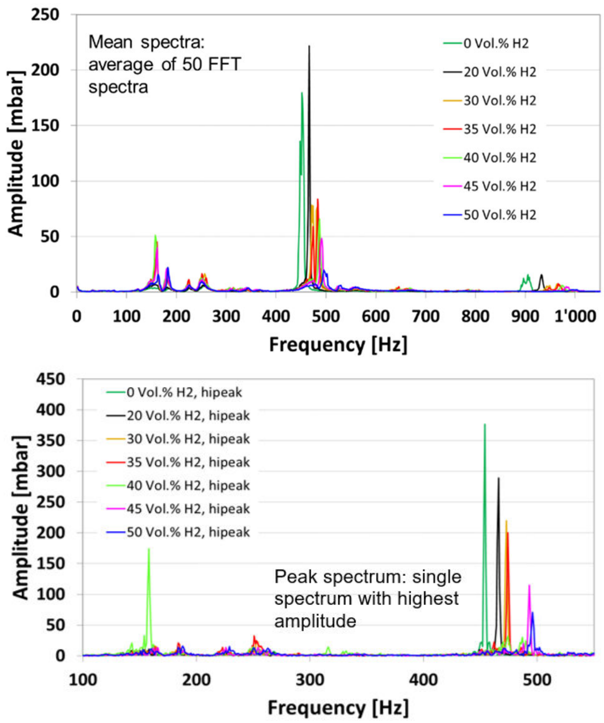


FIGURE 9: INFLUENCE OF HYDROGEN ADDITION ON THERMOACOUSTICS AT BASE LOAD CONDITION.

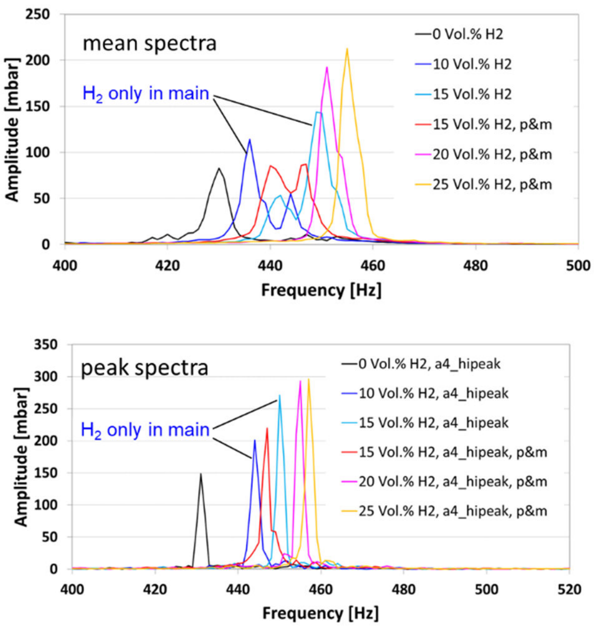


FIGURE 10: INFLUENCE OF HYDROGEN ADDITION ON THERMOACOUSTICS AT PART LOAD CONDITION.

Emissions: The NO_x and CO emissions measured at base load and part load conditions and different hydrogen contents are given in Figure 11. One should keep in mind that these runs were performed while keeping the adiabatic flame temperature constant. At base load condition and H_2 contents of up to 40 vol%, NO_x is almost constant. For higher H_2 contents NO_x decreases. This behaviour at H_2 contents up to 40 vol% is related to an almost unchanged flame position and heat release zone and therefore constant residence time in the high temperature zone known to be relevant for thermal NO formation. For higher amounts of hydrogen, the flame shape and heat release zone are getting more compact thereby lowering the residence time in high temperature zone resulting in a lower thermal NO formation. In addition, fuel blends with higher amounts of hydrogen do mix more rapidly with the oxidizer (combustion air) because of much higher diffusivity of hydrogen versus natural gas. Although turbulent mixing is most likely still the dominant driver for fuel/air mixing, the higher diffusivity of hydrogen additionally helps to improve the level of premixing resulting in lower NO_x values.

A moderate decrease of the CO emissions with increasing hydrogen content in the fuel is observed at base load condition. This is attributed partly to a substitution of carbon by hydrogen in the fuel. In addition, the longer residence time in the post flame region due to the upstream movement of the flame and heat release zone supports the CO oxidation thereby lowering the CO emission.

The CO emissions at part load condition strongly decrease with an increase of hydrogen in the fuel. The main reason for this is the better flame stability associated with a higher hydrogen amount in the fuel thereby supressing the CO formation which is known to be critical at part load conditions close to lean blow-out.

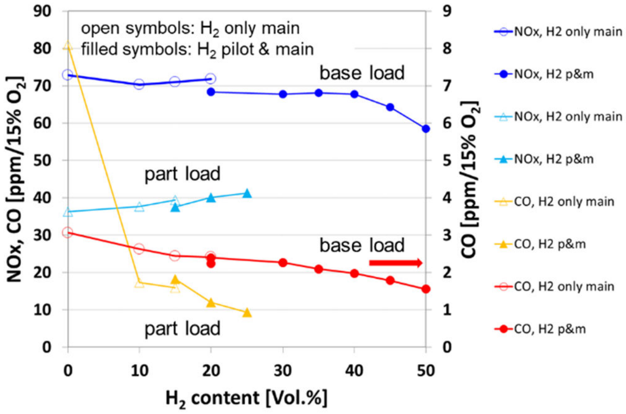


FIGURE 11: INFLUENCE OF HYDROGEN ADDITION ON NOx AND CO EMISSIONS.

At part load condition, the NO_x emission slightly increases with H_2 content. However, this increase is most likely within the measurement error of about 1-2 ppm.

In Figure 11 it is somewhat obvious that the NO_x emissions are slightly higher in the case of adding hydrogen only in the main fuel line than the values for adding H_2 in the pilot lance and main fuel line. The reason for this is a higher level of premixing achieved in the pilot flame when adding hydrogen to the pilot lance. Thereby the contribution of the diffusion type flame in the pilot to the overall NO_x formation is reduced.

3.2 Engine tests

The test campaign was motivated by the investigation of the ability of burning hydrogen with natural gas in an existing industrial gas turbine without any hardware modifications. In addition, the impact of hydrogen on the gas turbine operational behavior is assessed with respect to combustion stability, emissions and overall performance. On high level the following tests are conducted:

- Evaluation of safety limits of NG/H_2 blend combustion with H_2 ramping-up 2.5 vol% at base load and constant heat input with a maximum of 25 vol% H_2
- Finding the safe limits of NG/H_2 blend combustion with ramping up 2.5 vol% at part load and constant heat input
- Investigation of NG/H_2 blends with ramping up at base load and constant gas flow
- Exploring combustion tuning effects at base load and different hydrogen contents
- Exploring combustion tuning effects at part load and different hydrogen contents
- Transient base load and part load operation at different hydrogen percentages.

The tests covered 9 days in total. During the test, the following parameters are monitored to help intervene in case of negative impact of hydrogen addition on the installation:

- Emissions: NO_x & CO
- Power profiles and stability
- Gas turbine efficiency
- Temperatures and pressure at various hydrogen blends
- Combustion dynamics
- Active monitoring of hydrogen content by gas chromatography

All tests have been performed at steady state conditions (part load or base load), and no load gradients have been performed while the hydrogen was co-injected with the natural gas fuel.

Impact on power output and efficiency at constant heat input: The heat input of the gas is kept constant during the test in order to keep the base load output similar. As the volumetric energy density of hydrogen is about one-third of natural gas, the gas flow supplied to the gas turbine combustor will be increasing by increasing the hydrogen content.

Figure 12 shows the expected increase of gas flow by increasing the hydrogen content. Up to 20 vol% of hydrogen, the total gas flow will increase by ≈17% (orange line), while the natural gas flow decreases by ≈7%.

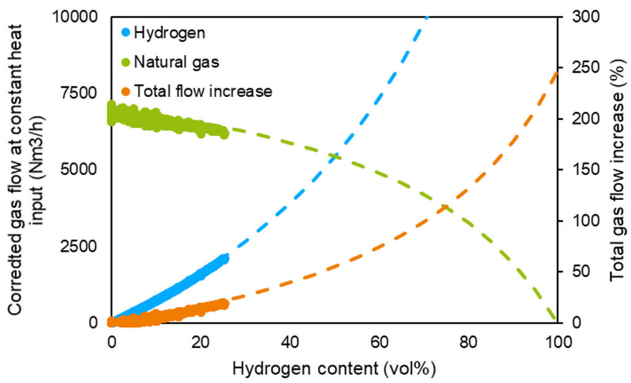


FIGURE 12: CORRECTED GAS FLOW AT CONSTANT HEAT INPUT.

For comparison of the different tests, the base load power output and efficiency are corrected by means of the correction curves to ISO conditions. Figure 13 shows the corrected power output and efficiency with respect to the hydrogen content. The open dots indicate stable and time averaged data points, while the blue dots are corrected per time sample (and thus instantaneous – mostly quasi stationary measurements).

It can be seen that hydrogen has no impact on power output and efficiency when the heat input is controlled.

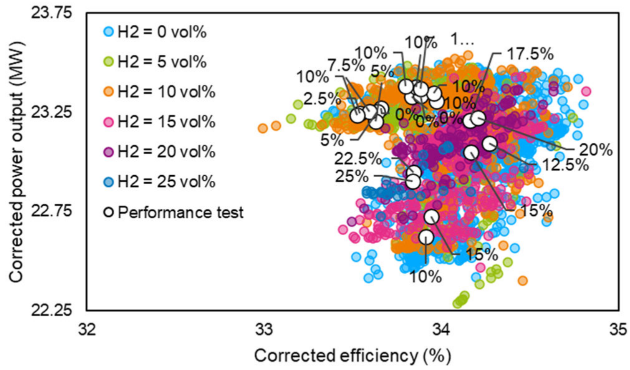


FIGURE 13: CORRECTED POWER OUTPUT AND EFFICIENCY WITH RESPECT TO THE HYDROGEN CONTENT FOR BASE LOAD CONDITIONS

Figure 14 shows the power output and efficiency at part load conditions (60% load) as a function of the hydrogen content. Similar to the observation at base load condition, no impact on of hydrogen on performance is observed.

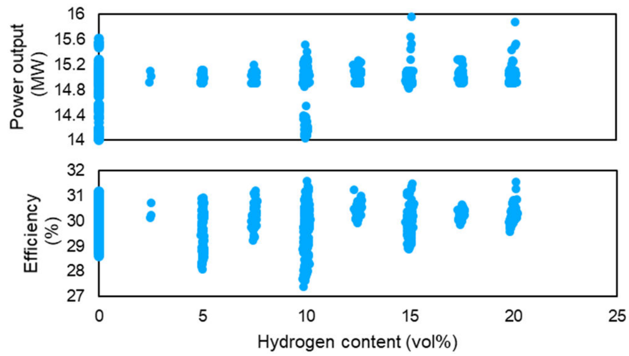


FIGURE 14: POWER OUTPUT AND EFFICIENCY WITH RESPECT TO HYDROGEN CONTENT AT PART LOAD (60%).

Impact on power output and efficiency at constant volumetric gas flow: In addition to the previously discussed test results for a constant heat input, one test keeping the gas flow constant is presented in the following section. At 10 vol% of hydrogen a reduction of power output of ≈7% is expected, while the gas volumetric flow is kept constant. Figure 15 shows the impact on power output and efficiency at this condition. The power output decreased by approximately 7% at 10 vol% hydrogen. No significant impact on efficiency is observed.

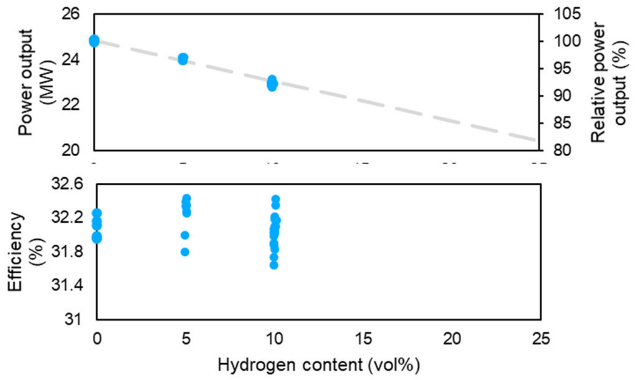


FIGURE 15: POWER OUTPUT AND EFFICIENCY AT BASE LOAD AND CONSTANT GAS FLOW

Emissions: When operating on natural gas, the NO_x emissions of the engine are just below the legislation emission limit of 50 mg/Nm^3, and therefore very little margin with respect to this limit is left.

At base load, the impact of hydrogen addition to natural gas increases the NO_x emissions at a rate of around 1 mg NO_x per 1 vol% of hydrogen, and this for the full range of tested hydrogen concentrations – up to 25 vol% H_2 (Figure 16). At the same time no positive effect of hydrogen addition on CO emissions is observed as the CO values at base load are already for pure natural gas combustion close to zero.

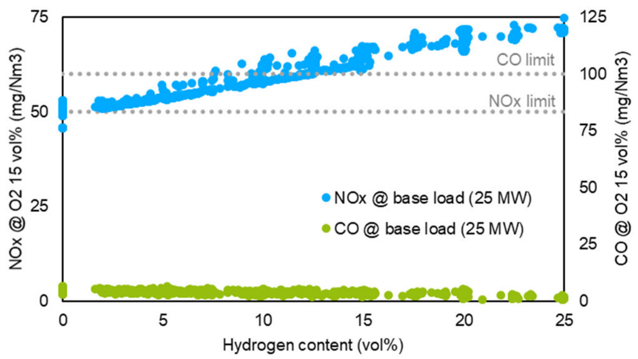


FIGURE 16: EMISSIONS AS A FUNCTION OF HYDROGEN CONTENT IN THE FUEL FOR THE GAS TURBINE OPERATING AT BASE LOAD

At part load, it is typically the CO emissions that become the limiting factor. CO emissions typically increase when approaching lean blow-out. Adding hydrogen to the fuel CO emissions decrease rapidly as shown in Figure 17. It is known that adding small amounts of hydrogen can already significantly improve the flame stability and therefore the CO emissions. In addition, substituting natural gas with hydrogen in the fuel does lower the carbon content in the fuel which also results in lower CO emissions, although this effect is not that big for these small amounts of hydrogen added.

On the other hand, NO_x emissions increase with higher hydrogen content in the fuel. Without tuning the NO_x emission limit is exceeded around 15 vol% H_2.

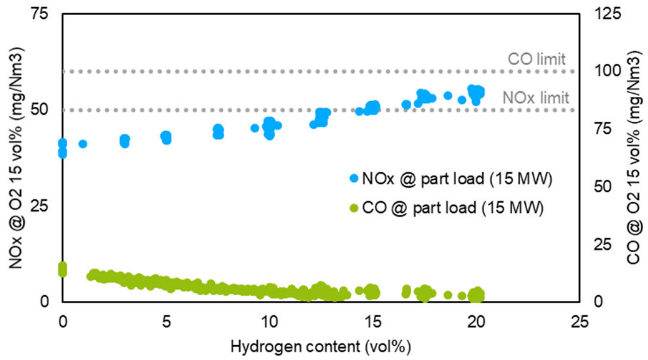


FIGURE 17: EMISSIONS AS A FUNCTION OF HYDROGEN CONTENT FOR THE GAS TURBINE OPERATING AT PART LOAD (15 MW).

4. SUMMARY AND CONCLUSIONS

The hydrogen co-combustion tests have been very successful. Starting from the single burner tests performed at DLR, ENGIE had sufficient confidence to execute full engine tests while the on-site production was continued.

The following conclusions are derived from the **single burner tests**:

- No flashback event observed in the investigated parameter range (base load, part load and H_2 contents up to 50 vol%)
- For moderate H_2 contents (H_2 < 30 Vol.%):
  - Minor influence on flame position / heat release zone and therefore on wall temperatures is found
  - NO_x emissions are only slightly affected
  - CO emissions strongly decrease
- For higher H_2 contents (H_2 > 30 Vol.%):
  - Significant influence on flame position and shape of heat release zone and therefore on wall temperatures is found
  - NO_x (@base load) decreases for H_2 > 40 Vol.%. The reason is a lower thermal NO formation due to a shorter residence time in the high temperature zone because of a more compact flame shape and heat release zone.
  - CO emissions decrease (strongly @ part load, moderately @ base load)
- Thermo acoustics
  - No high-frequency pulsations (f > 1 kHz) observed in the investigated parameter range
  - Shift to higher frequencies observed with H_2 addition
  - Pressure amplitudes change with increasing H_2 content (decrease @ base load, increase @ part load)

Full engine tests: The mixing skid performed very well and the hydrogen was mixed and co-combusted without negative impact on operations, i.e. no start/stop or trip.

Technically, the present study showed that hydrogen co-combustion with natural gas is safely possible. Today, discussions of gas grid operators are ongoing of adding up to 15-20 vol% hydrogen in the natural gas grid. It is clear that the ENGIE unit is H_2-ready without any modifications to the gas turbine hardware and that the unit can be operated safely with these hydrogen contents. The challenge today however is the availability of hydrogen on-site and at acceptable costs. The following lessons learned were derived:

- The Siemens SGT-600 2nd generation gas turbine is found to be H_2-ready up to 25 vol%, without any modification on the gas turbine hardware and any negative impact on operation (power output and efficiency).
- With respect to decarbonization it is demonstrated that a CO_2 reduction of 9 % is achievable when running on natural gas with 25 vol% H_2 in comparison to pure natural gas operation.
- The project also showed that NO_x emissions increase with increasing H_2 content in the fuel, as also expected for other GTs. However, higher NO_x emissions can be avoided by tuning the combustor. During the test at 10 vol% hydrogen NO_x emission could be reduced to the level of 100% NG with the help of combustor tuning, adapting only the pilot/main fuel ratio.
- CO emissions are stable and very low at base load and significantly decreased at lower load conditions. The addition of hydrogen stabilized the flame resulting in lower CO emissions. This has also a positive effect on combustion dynamics, which are significantly reduced by addition of hydrogen.

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