Hydrogen Co-Firing in Siemens Low NOx Industrial Gas Turbines

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Abstract

Hydrogen is a CO₂ free fuel that has the potential to become a future energy carrier simply by feeding it into the existing natural gas grid. Hydrogen is also present in waste gases from refineries, process gases from chemical industry or syngas from gasification of coal or biomass. Gas turbines offer a highly efficient energy conversion of gaseous fuel to electric power or mechanical drive. Introducing hydrogen in the fuel to a gas turbine with premixed low NOₓ systems, such as Siemens industrial gas turbines SGT-600 (25 MW), SGT-700 (33 MW), SGT-750 (41 MW) and SGT-800 (53 MW), could potentially induce flashback. The biggest technical challenge with hydrogen compared to natural gas is its high flame speed. Today Siemens offer the standard burner for fuels up to 15 vol% of H₂. Siemens has in continued development efforts enabled operation on higher hydrogen contents with a slightly modified burner. This paper reports the latest achievements of Siemens ongoing development to allow for hydrogen contents in natural gas higher than 40 vol% in the 3rd and 4th generation dry low emission (DLE) combustion systems. Additive manufacturing, 3D printing, is used for rapid prototyping of burner hardware.

A test from 2014 using the 3rd generation DLE burner with hydrogen feed to one burner in a gas turbine is reported. Combustion monitoring techniques and measurements to check flame behavior and assess flashback potential of the tested fuel compositions are described. The test proved the capability of the concept burner to operate with at least 45 vol% hydrogen in natural gas. It was also concluded that the NOₓ emissions could be kept below 24 ppm@15%O₂ at 70-100 % gas turbine load with the hydrogen rich fuel. Normal operation including transients and load cycling was also demonstrated with the hydrogen rich fuel.

The hydrogen capacity of the 4th generation DLE burner has been evaluated in a combustion test rig. The testing shows that hydrogen levels up to 45 vol% are achievable without significant increase in combustion dynamic levels. The NOₓ emissions may be tuned to single digit for hydrogen contents below 25 vol% and below 20 ppm for hydrogen levels below 35 vol%.
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Nomenclature

CO₂  Carbon Dioxide  
DLE  Dry Low Emission  
DLR  Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)  
EBIT  Experimental Burner in Test Engine  
GU  Gas Unit  
H₂  Hydrogen  
LNG  Liquefied Natural Gas  
NG  Natural Gas  
NOₓ  Nitrogen Oxides  
O₂  Oxygen
1. Introduction

Load flexible and fast starting gas turbines can support and bridge the transfer to a sustainable and renewable power generation. Hydrogen is a CO₂ free fuel that has the potential to become a future energy carrier simply by feeding it into the existing natural gas grid. A hydrogen fired gas turbine emits only water and the larger the share of hydrogen in the fuel split, when co-firing, the lower the CO₂ emissions. Traditionally gas turbines with diffusion flames, so called conventional combustion systems, have been used to fire fuels with high amounts of hydrogen. Since diffusion flames are hot the NOₓ emissions are inherently very high and water injection is commonly used [i] to comply with not too stringent emissions demands such as for instance World Bank regulation.

Siemens has since several years developed their gas turbines to handle co-firing of hydrogen in premixed flames, so called dry low emissions (DLE) combustion systems which enables about 100 times lower NOₓ emissions without water injection in the combustor [ii, iii]. Hydrogen is today present in waste gases from refineries, process gases from chemical industry or syngas from gasification of coal or biomass.

2. Siemens industrial gas turbines

Eight so called 3rd generation DLE burners are shown on left hand side in Figure 1 and this burner consists of a split cone forming four air slots where main gas is injected followed by a mixing section. The pilot fuel injection is positioned at the burner tip. This burner is used as standard in the annular combustors of SGT-700 (33 MW) and SGT-800 (53 MW) and is also an available option for the SGT-600 (25 MW) when very low emissions are required. The 3rd generation DLE system delivers below 15 ppm NOₓ emissions on natural gas and 42 ppm NOₓ on liquid fuel. The burners in the figure are manufactured by 3D printing [iv], a technique that enables reductions in lead time, material consumption and fast prototyping of customer tailored/fuel adaption in the burner design.

The 4th generation DLE combustion system developed for the SGT-750 (41 MW) is a can design, right hand side in Figure 1 and the burner consists of a main swirler with a split plate that separates the main 1 and main 2 channels, a central pilot and a central combustor. The main flame is stabilized in the quarl by a strong central recirculation zone.

![Figure 1: 3D printed 3rd generation DLE burner fronts (left) and cold flow model of the 4th generation DLE burner (right)](image-url)
3. Hydrogen as a fuel

The flame speed of pure hydrogen is almost ten times higher than for methane which increases the risk of flashback. In addition, the flammability limit is wider for hydrogen than for methane. In other words, hydrogen in air can be ignited and burn at a much wider range than methane. Although this fact increases the risks of handling hydrogen, in general it is in fact positive for a lean premixed combustion system because flames can be sustained at leaner conditions than for natural gas. In general, increased reactivity of fuels may lead to increased lean combustion stability particularly at part load.

Fundamental understanding of the combustion behavior of lean premixed combustion of hydrogen cofired with natural gas and other typical gas turbine fuels are developed in parallel to burner development [v, vi, vii, viii and ix]. Advanced numerical modelling in combination with detailed measurements in flames is gaining insight into the combustion situation. Figure 2 illustrates numerical simulation of the Siemens 3rd generation DLE burner to the left with natural gas (a) and 80 vol% H2 in natural gas (c). It is predicted that the flame shape changes and the central part of the flame moves upstream the burner, into the fresh mixture of air and fuel. This is also verified in experiments seen on the right hand side for natural gas (b) and for 80 vol% H2 in natural gas (d). Laserbased measurements of the combustion radial OH indicates presence of flame and the gradient of OH from the fuel/air side and downstream indicates the flame front. Also here it is seen that the hydrogen rich flame has a tendency to move upstream the burner.

![Comparison of numerical simulation of time averaged “completed combustion reaction” with probability density function of measured OH radical concentration gradient [v]](image-url)
4. Fuel flexibility testing

Full scale fuel flexibility testing in gas turbines are challenging since fuel amounts are large: a 30 MW engine needs about 7,000 kg of hydrocarbon fuel per hour and a full scale test could typically last for 3-6 hours, meaning up to 40,000 kg of testing fuel to be handled. Transport and storage are not easily organized. Also the costs and efforts are substantial for acquiring and blending unusual fuels, not to mention how to get local authorities and fire brigades approval for handling such large quantities of special fuel mixtures. The Siemens new approach for fuel flexibility testing has been to combine the single burner testing with a full scale engine test to give a cost effective and flexible solution; experimental burner in test engine (EBIT). This is accomplished by using a separate feed of testing fuel to one or more burners in a standard gas turbine installation where the other burners use standard fuel from standard fuel system for engine operation [x].

Figure 3 shows a schematic of EBIT, where natural gas (NG) is bled from the main gas supply to the engine and then mixed with hydrogen. The hydrogen/natural gas mix can be fed to three gas injection lines into the experimental burner in the test engine. The separate feed of testing fuel can be operated as a slave to engine governor heat demand, but can also be controlled independently. For monitoring operation the standard gas turbine instrumentation is complemented with optical probe and one additional emissions probe, see Figure 4.

The 4th generation DLE was tested for fuel flexibility at the single burner high pressure test facility at DLR (German Aerospace Center) in Cologne, Germany.

Figure 3: Schematic drawing of the single burner feed, EBIT [x]

Figure 4: EBIT concept implemented in the SGT-700 engine[x]
5. Hydrogen in the 3\textsuperscript{rd} and 4\textsuperscript{th} generation DLE systems

3\textsuperscript{rd} generation DLE

Hydrogen enriched natural gas was verified during engine operation in 2012 [iii, xi]. Stable operation could be achieved using hydrogen fractions around 30-40 vol\%, resulting in a general release of up to 15 \% for the 3\textsuperscript{rd} generation DLE system, with a possibility to accept higher fractions on a case by case basis. Further analysis of the 2012 hydrogen tests indicated that minor modifications to the standard burner could improve the hydrogen capability. Changes were implemented and new tests with modified burners were performed during 2014. A criterion for acceptable burner modifications was that natural gas capability should be kept, with acceptable emissions. The test procedures during the 2014 tests were the same as during 2012, with single burner testing in an engine.

Customer enquiries about hydrogen rich fuels often come from a need for disposal of a waste stream from a chemical plant or a refinery. The plant often also has a need for mechanical or electrical power. Two types of operating situations can be envisaged with either a constant hydrogen flow and the engine power is varying or a constant engine power with a varying hydrogen flow. An example of a test addressing the first situation is shown Figure 5.

![Figure 5: SGT-700 test with constant hydrogen consumption at variable engine power [xii]](image)

The engine load is varied with standard ramp between 27 and 10 MW with a constant flow of hydrogen corresponding to approximately 0.5 ton/h for an SGT-700. It can be seen that the hydrogen content in the fuel varies between 50-75 \% as a consequence of the varying load. The high load case is run with 50-60 \% hydrogen in the fuel. NO\textsubscript{X} emissions variation is a consequence of the variation of pilot depending on load. Lower load needs higher pilot for stability, which gives higher NO\textsubscript{X}.

The influence of hydrogen content on NO\textsubscript{X} emissions is shown in Figure 6 where normalized NO\textsubscript{X} is shown at full load without pilot. A small increase of NO\textsubscript{X} can be seen as hydrogen content increases, but the increase is only significant above 45 \% hydrogen.
The 2014 tests confirmed the possibility to run the SGT-700 on high hydrogen fuels with results indicating that 40-50 % H\textsubscript{2} is possible at high loads. At lower loads, higher hydrogen content is possible as can be seen in Figure 5. At 10 MW load, 100 % H\textsubscript{2} was tested and it was fully possible to run, but the hydrogen flow had to be doubled and NO\textsubscript{X} emissions were about 60 % higher than the high load emissions.

4\textsuperscript{th} generation DLE

Testing of SGT-750 combustion systems have been performed in various scales [xiii, xiv and xv] The combustion system was also tested on gas mixtures of CO and H\textsubscript{2}, which combines the low auto-ignition energy of carbon monoxide with the high flame speed of hydrogen (see Figure 7). These types of mixtures are usually referred to as syngas fuels. The SGT-750 combustion system was tested at several load conditions and the burner was tuned at NO\textsubscript{X} emissions below 15 ppmv at 15 % O\textsubscript{2} for loads above 50 % of base load and single digit NO\textsubscript{X} for loads above 80 %. The concentration of hydrogen was reduced while increasing engine load in order to maintain NO\textsubscript{X} emissions around 10 ppmv.

Figure 8 shows the test results for the SGT-750 operation at engine full load conditions with mixtures of natural gas and hydrogen. The SGT-750 burner operation could be tuned to achieve around 10-12 ppmv NO\textsubscript{X} at15 % O\textsubscript{2} while having up to 25 vol% of hydrogen in natural gas fuel. The NO\textsubscript{X} emissions could be tuned below 20 ppmv at15 % O\textsubscript{2} for hydrogen concentrations up to 35 vol%. The NO\textsubscript{X} emissions were increasing with higher hydrogen concentrations. This was caused by the need to increase the pilot fuel ratio, but the tests showed that it was still possible to tune the burner operation in order to achieve NO\textsubscript{X} below 25 ppmv at 15 % O\textsubscript{2} for hydrogen concentrations above 45 vol%.

The low frequency combustion dynamics were reasonably low for all the hydrogen gas mixtures tested. When comparing with pure natural gas levels it is not possible to see a significant increase as shown in figure 8. The test results also contain test points taken just after the hydrogen concentration was increased and those show higher NO\textsubscript{X} emissions. At hydrogen concentrations corresponding to 18 vol% and 47 vol% the fuel splits were altered to explore the NO\textsubscript{X} and combustion dynamics response showing the low NO\textsubscript{X} capability also at high hydrogen concentrations.

Figure 6: NO\textsubscript{X} vs hydrogen content during the SGT-700 test; full load and no pilot fuel [xii]

![Figure 6: NO\textsubscript{X} vs hydrogen content during the SGT-700 test; full load and no pilot fuel](image)
Figure 7:  Tested fuel compositions in 4\textsuperscript{th} generation DLE burner [xv]

Figure 8:  SGT-750 operation at engine full load conditions with mixtures of NG and hydrogen [xv]
6. Conclusions

Data gathered indicates that Siemens medium sized gas turbines can be offered to customers with a wider fuel flexibility according to table below.

<table>
<thead>
<tr>
<th>Gas Fuel Constituents</th>
<th>SGT-800</th>
<th>SGT-750</th>
<th>SGT-700</th>
<th>SGT-600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane, CH4</td>
<td>100 mole%</td>
<td>100 mole%</td>
<td>100 mole%</td>
<td>100 mole%</td>
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<tr>
<td>Ethane, C2H6</td>
<td>100 mole%</td>
<td>35 mole%</td>
<td>100 mole%</td>
<td>100 mole%</td>
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<tr>
<td>Propane, C3H8</td>
<td>100 mole%</td>
<td>30 mole%</td>
<td>100 mole%</td>
<td>100 mole%</td>
</tr>
<tr>
<td>Butanes and heavier alkanes, C4+</td>
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<td>15 mole%</td>
<td>15 mole%</td>
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<tr>
<td>Hydrogen, H2</td>
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<td>Inerts, N2/CO2</td>
<td>50/40 mole%</td>
<td>50/40 mole%</td>
<td>50/40 mole%</td>
<td>50/40 mole%</td>
</tr>
</tbody>
</table>

Table 1: Range of gas fuel constituents for gas turbine types SGT-600, SGT-700, SGT-750 and SGT-800
References

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