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Co-firing with hydrogen in industrial gas turbines

(Sameldning med vätgas i industriella gasturbiner)

Mats Andersson, Jenny Larfeldt, Anders Larsson

"Catalyzing energygas development for sustainable solutions"

SGC Svenskt Gastekniskt CenterAB

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Energimyndigheten
Siemens Industrial Turbomachinery AB
Infraserv GmbH & Co. Höchst KG

Postadress och Besöksadress
Scheelegatan 3
212 28 MALMÖ

Telefonväxel
040-680 07 60

Telefax
0735-279104

E-post
info@sgc.se

Hemsida
www.sgc.se

Svenskt Gastekniskt Center AB, SGC

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Malmö 2013

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Martin Ragnar
Chied Executive Officer

Authors' foreword

This work has been performed by Siemens and Infraserv Höchst. Infraserv has a potential to co-fire hydrogen with natural gas in their SGT-800 gas turbines and they are exploring this possibility. The co-firing philosophy depends on the hydrogen concentration that the SGT-800 gas turbine is able to handle. Siemens has performed a test in an engine in order to find a safe limit for hydrogen in the fuel gas. The reason for such limit is explored together with the research partners Combustion Physics at Lund University (LTH) and the Swedish Defense Research Agency (FOI). LTH have contributed by applying advanced measurement techniques in Siemens atmospheric combustion test rig and also with detailed chemical kinetic modeling. FOI has made detailed numerical modeling of the Siemens burner.

The reference group following this project has been;
Anna-Karin Jannasch, SGC
Anders Molin, E.ON Gas Sverige
Jenny Larfeldt, Siemens
Anders Larsson, Siemens

Summary

Hydrogen is a CO_2 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 SGT-700 and SGT-800, could potentially induce flashback. The biggest technical challenge with hydrogen compared to natural gas is its high flame speed.

The purpose of the project is to find the maximum concentration of hydrogen in natural gas that SGT-700 and SGT-800 can handle with standard combustion system and also increase our knowledge on what is setting this limit.

A survey of relevant combustion properties of hydrogen and hydrogen/methane mixtures indicates that up to 35 % by volume H_2 can be mixed into natural gas without any dramatic changes of the combustion situation and thus no dramatic change in NO_x emission. This is in accordance with the emissions measured during the actual test performed in this project. The test was performed on a standard SGT-700 in Finspong with so called “single burner feed” of natural gas with increasing amount of hydrogen.

Preceding work is briefly included in this report and numerical simulations indicate that the flame will move closer to the burner exit as the hydrogen concentration increases to 60 % by volume. This effect is amplified by pressure which is demonstrated by combustion testing at atmospheric conditions with the gas turbine burners allowing operation on 100 % hydrogen.

Two burner hardwares with different fuel distribution, configuration 1 and 2, were tested during the four day exercise. The predicted tendency for the flame to move closer to the burner exit was seen in the test and particularly for burner configuration 1. Interestingly, burner configuration 2 instead showed a tendency more related to pilot flame shifting. By comparing the two Siemens has confidence in finding the optimum burner configuration for future hydrogen development.

Results of tests in brief;

- Stable operation at near 40 % by volume H_2 has been demonstrated.
- Tendency to flame shifting was seen and understanding of the dependencies has increased.
- The stability of the hydrogen feeding system was not as accurate as desired and needs to be improved particularly for higher hydrogen contents.

Based on the test Siemens has already increased the allowed hydrogen content in the standard SGT-700 and SGT-800 today to 15 % by volume of H_2.

Sammanfattning på svenska

Vätgas är ett koldioxidneutralt bränsle med potential att bli en framtida energibärare som kan matas in det på existerande naturgasnätet. Koncentrationer på upp till 10 volymprocent väte är det som för närvarande diskuteras i Europa. Utöver detta så ser Siemens en ökande trend på förfrågningar för gasturbindrift på gaser som innehåller väte. Exempelvis kan det vara olika restgaser från raffinaderier, processgaser från kemisk industri eller syntesgas från förgasning av exempelvis kol eller biomassa.

Gasturbiner ger en effektiv omvandling från gasbränsle till elkraft eller mekanisk drivning. Siemens gasturbiner SGT-700 (33 MW) and SGT-800 (50 MW) offereras med förbränningssystem för låg NOx där bränsle och luft blandas uppströms i brännaren innan flamzonen. Därmed uppnås låga emissioner utan insprutning av vatten för sänkning av flamtemperaturen.

Genom att introducera väte i bränslet till en gasturbin med förblandat förbränningssystem, såsom i Siemens SGT-700 och SGT-800, ökar risken för ”flashback”, dvs. skadlig flametablering uppströms i brännaren. Den största tekniska utmaningen med väte jämfört med naturgas är dess höga flamhastighet.

Syftet med föreliggande projekt är att hitta maximal koncentration av väte i naturgas som SGT-700 och SGT-800 kan hantera med standard förbränningssystem samt att öka vår kunskap om vad som sätter denna begränsning.

En översikt av relevanta förbränningsegenskaper för väte och väte/metanblandningar indikerar att upp till 35 volymprocent väte skulle kunna mixas i naturgas utan några dramatiska förändringar i förbränningsbeteende och inte heller några signifikanta skillnader i emissioner av NOx. Detta visar sig vara i linje med de emissioner som faktiskt uppmätts inom ramen för projektet.

Förberedande arbete som genomförts vid Siemens såsom atmosfäriska prov och numeriska simuleringar nämns kortfattat i denna rapport. Simuleringar och prov indikerar som förväntat att flamman flyttar sig närmare brännarens utlopp med ökande vätehalt. Denna effekt förstärks vid högre tryck där förbränning ej kan ske med 100 % väte såsom i de atmosfäriska proven.

Ett test genomfördes i en SGT-700 i Finspång med så kallad enbrännarmatning med naturgas med stigande innehåll av väte. En av maskinens 18 brännare byttes ut till en speciellt instrumenterad testbrännare med separat bränslematning. En delström av naturgas länkades av huvudflödet till leveransmaskinen och blandades med det aktuella testbränslet som i detta prov var väte. Blandningen matades sedan till testbrännaren som kunde styras separat från maskinens övriga 17 brännare.

Två olika brännarkonfigurationer, 1 och 2, användes i detta prov som genomfördes mellan den 18:e och 21:a september 2012. Båda konfigurationerna är väl kända för Siemens sedan tidigare intern provning. Under provet levererade maskinen cirka 30 MW till fasta lastbankar och förutom maskinens normala signaler loggades även extra temperaturer i testbrännaren, emissioner i ett stråk efter

brännaren samt det dynamiska trycket i testbrännaren. En boroskopkamera användes också för visuell observation av flamläge vid testbrännaren.

Drift på uppemot 40 volymprocent väte demonstrerades under provet. För de två brännarkonfigurationerna noterades att flamman tenderade att skifta läge för konfiguration 1 i själva huvudflamman medan pilotflamman var begränsande för konfiguration 2. Detta gav värdefull information för fortsatta utvecklingsinsatser med mål att verifiera högre koncentrationer med en optimal brännarkonfiguration.

Stabiliteten hos vätematningssystemet var inte helt tillfredställande under provet, speciellt inte vid högre halter väte. För fortsatta prover med ännu högre halter bör detta förbättras.

Baserat på provet så höjdes de tillåtna nivåerna i SGT-700 och SGT-800 till 15 volymprocent väte, vilket ligger väl över de nivåer på 10% som diskuteras för det europeiska gasnätet.

Content

1 Background

Hydrogen has the potential to become a future energy carrier in regions where there is an occasionally surplus of electricity production from wind and solar. It is already a fact that in some regions wind power cannot be distributed due to limitations on electric grid transmission and storage capacity. Design of new electric grids and for instance hydro or pressurized air storages are costly and therefore long term investments. For this reason there is a discussion and also some demonstrations already launched on possibilities to use surplus power to produce hydrogen by electrolysis and then to store this hydrogen until it is converted back to electricity. An alternative is to feed the hydrogen into the existing natural gas grid and thereby store, transport and convert it within the existing infrastructure. Concentrations up to 10% by volume of hydrogen are currently discussed in Europe.

Besides the above mentioned European discussion on hydrogen Siemens experiences an increasing trend in requests for gas turbines (GTs) operating on hydrogen containing gases. For instance it is waste gas from refineries, process gases from chemical industry or syngas from gasification of coal or biomass. There is often an opportunity to co-fire these gases with natural gas.

Siemens gas turbines SGT-700 (33 MW) and SGT-800 (50 MW) are offered with standard premixed low-NOx combustion systems where fuel and air are mixed upstream in the burner before combustion takes place. For fuels with high flame speed, such as hydrogen, there is an increased risk of flash back behavior. Experiments and modeling have lately shown that this burner is very fuel flexible.

For process industries such as Infraserv Höchst such fuel flexibility implies that the natural gas consumption can be reduced and thereby the emissions of CO_2.

2 Purpose

The purpose of the project is to find the maximum concentration of hydrogen in natural gas that SGT-700 and SGT-800 can handle with standard combustion system and also increase our knowledge on what is setting this limit.

Testing to be performed on a standard SGT-700 in Finspong with so called “single burner feed” of natural gas with increasing amount of hydrogen. During the test the emissions, flame position, combustion dynamics and temperatures are evaluated.

3 Combustion properties of hydrogen compared to natural gas

For premixed low NOx systems, the risk for flashback in the burner due to the high reactivity of hydrogen is the main concern. The technical challenges with hydrogen compared to natural gas are;

- The higher flame speed
- The higher adiabatic flame temperature
- The lower auto-ignition delay times
- The wider flammability range
- The increase in volumetric fuel flow rate

The lower heating value of hydrogen is 120 MJ/kg compared to 50 MJ/kg for methane.

3.1 Ignition delay time

The auto ignition delay time is experimentally measured for instance as illustrated in figure 1. In this figure the combustible mixture, not relevant for hydrogen mixtures discussed here, does not ignite until after approximately 2 ms which is then the ignition delay time. The ignition is in this case monitored by the pressure in the combustion vessel and also by the formation of combustion radicals[1]. Ignition delay times versus temperature for stoichiometric hydrogen and air mixtures are shown in figure 2. For a temperature of 700 °C, it can be seen that the ignition delay time is in the range of 0.3 ms. As an example for a premixed burner this means that the residence time of the premixed fuel and air upstream in the burner has to be shorter than 0.3 ms to avoid flashback. Now the temperature upstream in SGT-800 gas turbine burner is not 700 °C, but rather 400 to 450 °C which in figure 2 leads to much longer ignition delay times (outside the x-axis range). However the data in figure 2 is at 2 bar pressure and SGT-800 conditions is typically ten times higher, around 20 bars.

For mixtures of hydrogen and methane, data from literature indicate that the ignition delay times of the mixture can be linearized from the delay times for each component respectively as shown in figure 3. Ignition delay time for pure methane is about 20 ms and when hydrogen is introduced it decreases to about 8 ms. Compared to many heavy hydrocarbons this impact is not so significant – i.e. it is still the same order of magnitude for the ignition delay time.

[1] Combustion radicals are unsaturated intermediate species in combustion reactions only existing at the high temperatures related to ongoing combustion. They can be quantified using advanced laser based measuring techniques.

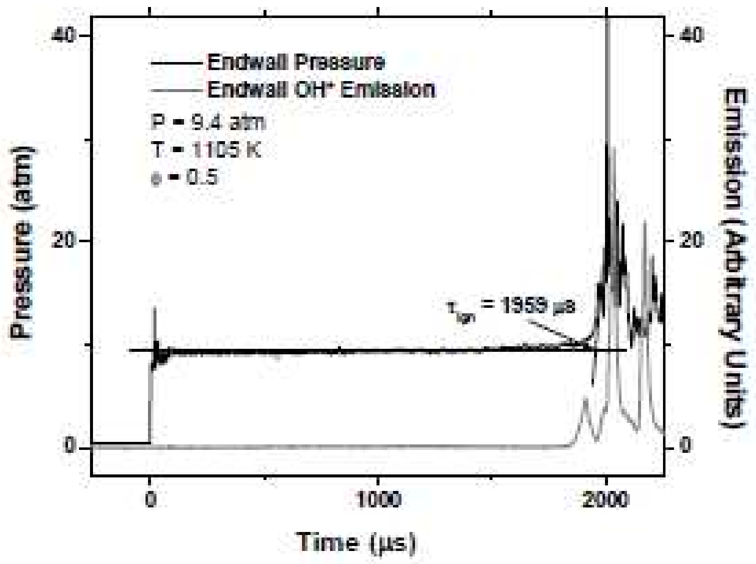

Figure 1. Typical recordings of pressure and emission traces for determination of ignition delay time. Illustrated here for a lean mixture of butanes at 9.4 atm and 1105 K [1].

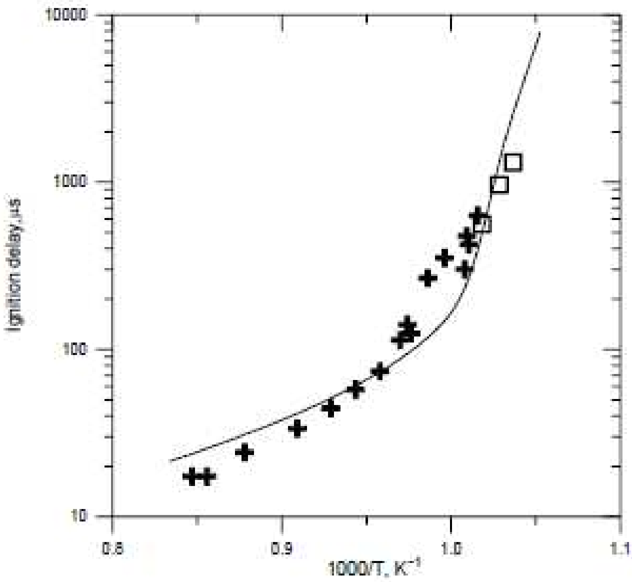

Figure 2. Ignition delay times in stoichiometric H_2 – air mixtures at 2 atm versus inverse temperature. Experimental data (+ and ▫) and modeling (line) [2].

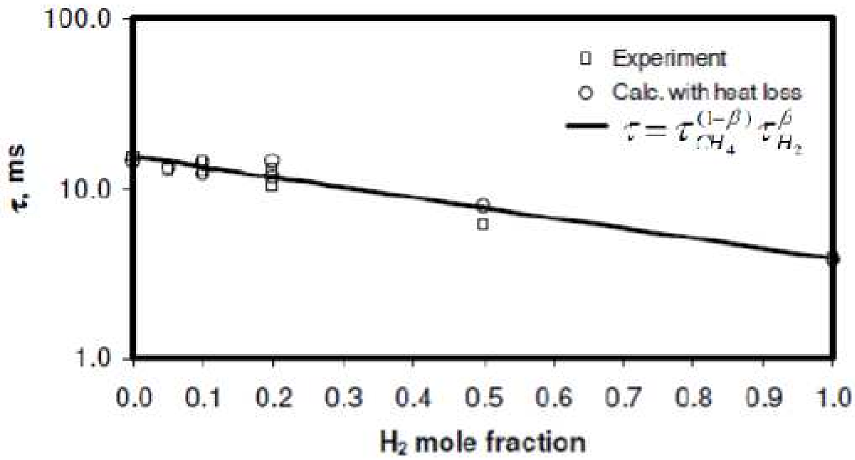

Figure 3. Ignition delay times for mixtures of hydrogen and methane at 33,5 atm and 995 K versus hydrogen content [3].

3.2 Flame speed

As shown in figure 4, the laminar flame speed for hydrogen burning with air is almost ten times higher than for methane burning in air. The peak adiabatic temperature is 155 degrees higher for the hydrogen flame than for a pure methane flame. Lean combustion conditions, such as in premixed gas turbine combustors where ϕ[2] is about 0.5, is not included in the figure but the flame speeds are generally lower and also the difference between hydrogen and methane is lower.

The fact that hydrogen combustion at rich conditions is faster and warmer than methane indicates that addition of hydrogen to the combustor can actually have a stabilizing effect and by that make the task for the pilot less critical. For instance the pilot fuel flames in the SGT-800 combustion system tend to be slightly richer in order to bring stability to the combustion situation. If hydrogen is present the stabilizing effect is increased for the same pilot fuel ratio.

For mixtures of hydrogen and methane the laminar flame speed will increase with increasing hydrogen content, which is well known and in agreement with literature. Up to about 40% H_2, see figure 5, the flame speed increases from 37 cm/s for pure methane up to 53 cm/s for a 40% H_2 mixture with methane. This is not a dramatic increase.

Also the flammability limit is wider for hydrogen than for methane, see table 1. 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 dry low emission (DLE) combustion system since flames can be sustained at leaner conditions than for natural gas.

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[2] ϕ is the stoichiometric air to fuel ratio divided by the actual air to fuel ratio. A ϕ of 0,5 means that twice as much air as needed is present in combustion.

Table 1 Flammability limits

Reactants	Flammability limits (vol-% fuel)		Stoichiometric composition
	Upper	Lower	(vol-% fuel)
H_2 + air	**4**	**75**	**28,5**
CH_4 + air	**5,3**	**15**	**9**

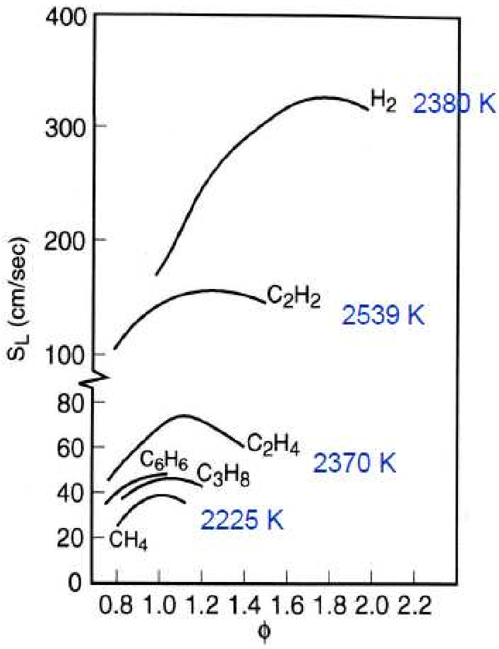


Figure 4. Laminar flame speed for various hydrocarbons and hydrogen versus stoichiometry. Adiabatic flame temperature in blue [4].

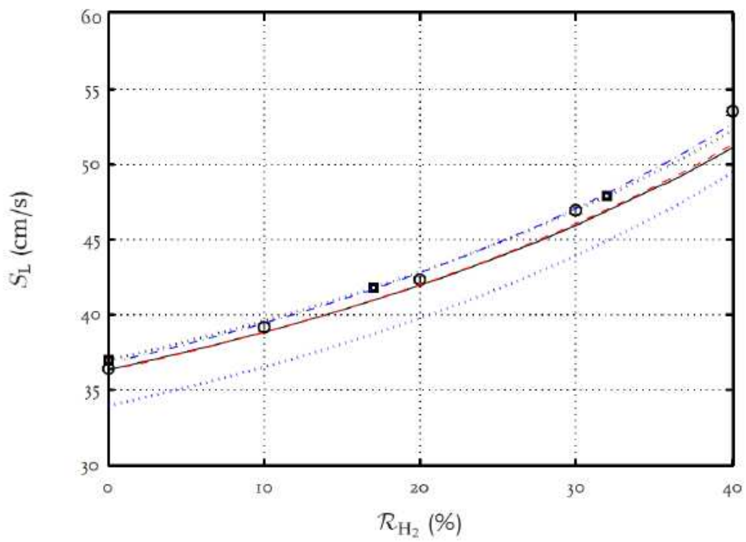


Figure 5. Experimental (dots) and numerical (lines) data of the laminar flame speed of stoichiometric methane-hydrogen-air flames versus hydrogen content [5].

3.3 Expected impact on NO_x emissions

The emission of NO_x from combustion is related to several formation reaction routes. For the case of natural gas, NO_x formation is promoted by high combustion temperatures (thermal-NO_x) and the concentration of hydrocarbons (prompt-NO_x). Figure 6 shows NO formation at adiabatic conditions and atmospheric pressure for mixtures of hydrogen in methane from 0 % by volume to 35 % by volume. As seen, the formation varies with stoichiometry for all mixtures. At rich mixtures, to the right in the figure, the prompt-NO_x formation is important and it can be seen that addition of hydrogen decreases the NO formation slightly. At stoichiometric mixtures, NO is formed as thermal-NO_x and thus formation increases with temperature. Since increasing hydrogen content means increase in adiabatic flame temperature the NO formation increases with hydrogen content. At lean combustion conditions, ϕ = 0,5 such as in SGT-800, the impact on NO formation from hydrogen does not have a clear trend. Therefore the NO_x emission is not believed to change significantly as hydrogen is mixed into the natural gas up to 35 % by volume H_2.

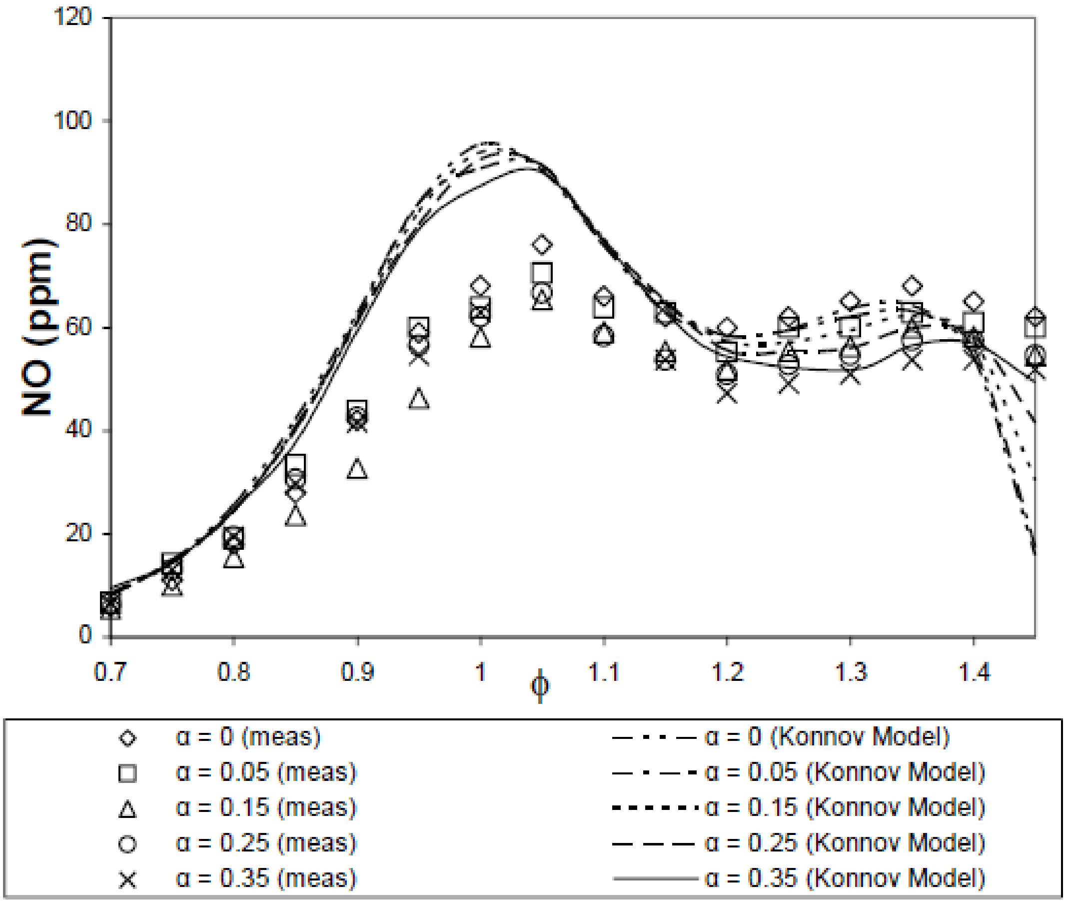


Figure 6. Production of NO versus stoichiometry for various mixtures of H_2 in CH_4 (α = molar ratio of hydrogen in methane) [6].

4 Preceding work with atmospheric combustion testing

The Siemens 3rd generation Dry Low Emission (DLE) burner is used in SGT-700 and SGT-800. This burner consists of a split cone forming four air slots where the main gas is injected followed by a mixing section with film air holes. Near the base of the cone, central gas or main liquid is fed and intensively mixed with the compressed air. The pilot fuel injection is positioned at the burner tip while central gas can be added through a lance in the center of the burner, see upper part of figure 7. In red is shown the fuel injection positions for main gas, central gas and pilot gas (the liquid system for dual fuel burners is not considered in this study). The locations for the performed Planer Laser Induced Fluorescence (PLIF) measurements by LTH are shown with green marking at the burner outlet.

The bottom part of figure 7 shows the main flow field inside and after the burner, where central, inner and outer recirculation zones are created in an annular combustion chamber. More information about this burner and the measurement techniques used can be found in the paper by Lörstad et al [7].

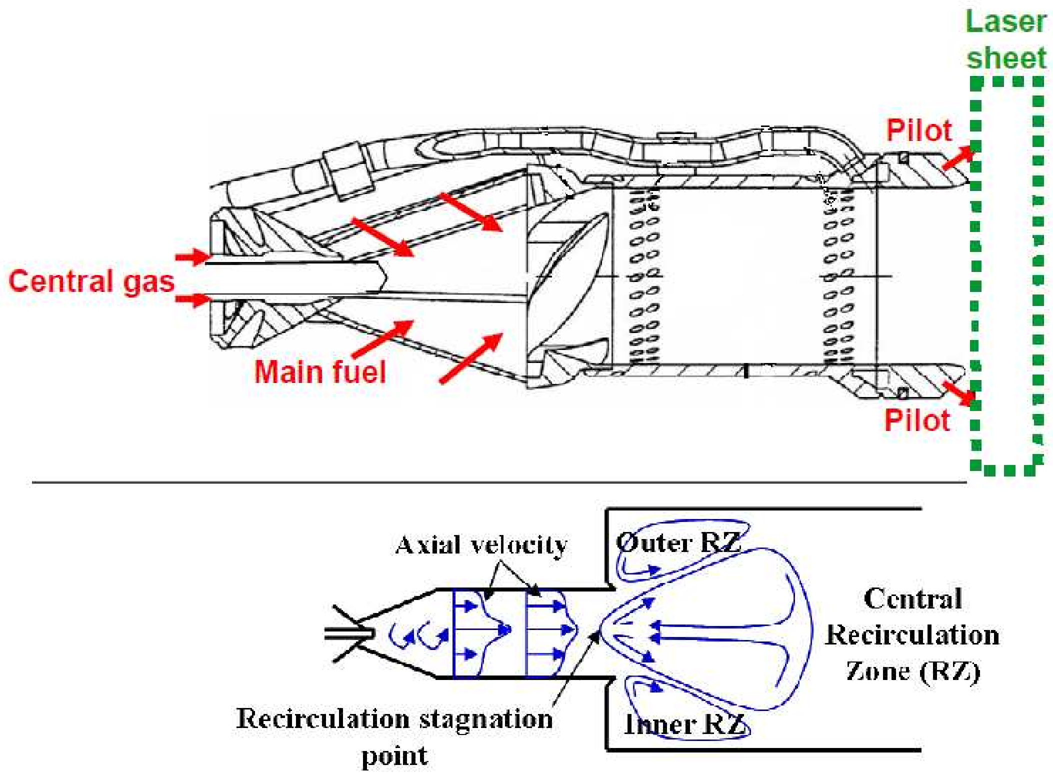


Figure 7. Overview of the basic principles of the SGT-700/800 burner. Top: Burner description and position of measurement region. Bottom: Flow description and recirculation zones.

Figure 8 shows the rig used for the investigation of hydrogen enriched natural gas in the SGT-700/800 burner and the burner position, the main flow passages and the locations of optical access are pointed out [7].

When operating the burner on increasing amounts of hydrogen the flame changes characteristics, see figure 9. Since this is a single burner atmospheric test rig the burner can be operated without supporting pilot up to 100 % H_2. The flame with high content of H_2 seems to be thinner indicating that the flame front is more distinct. This is also seen from the OH-radicals measurement in figure 10. The figure shows the averaged results of the OH measurements [8] where the flame seems to increase its radius as hydrogen content increases.

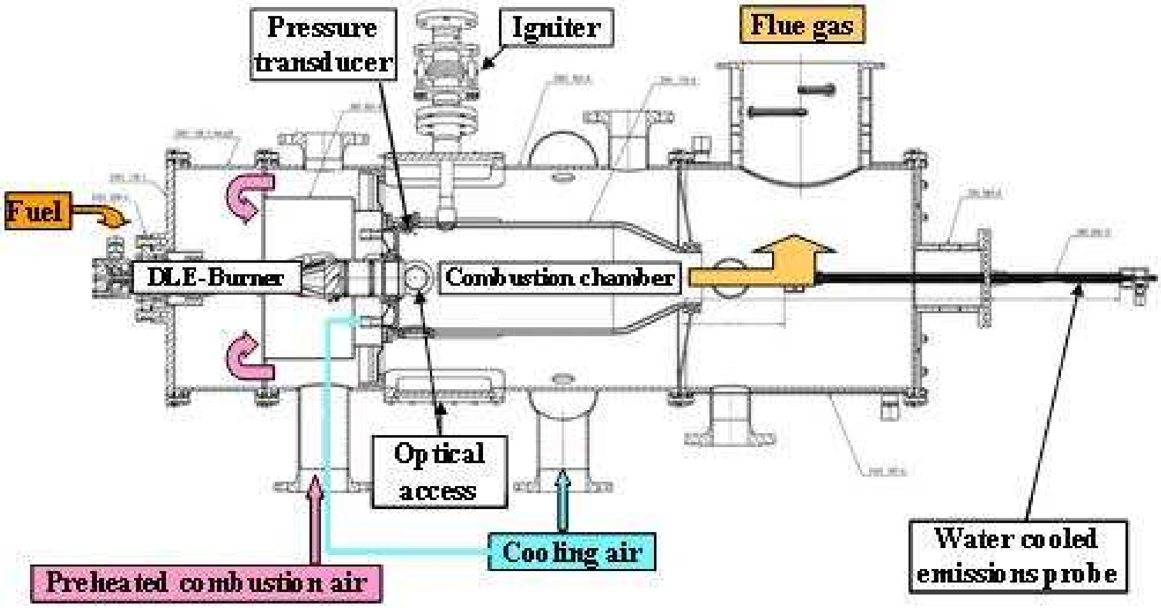
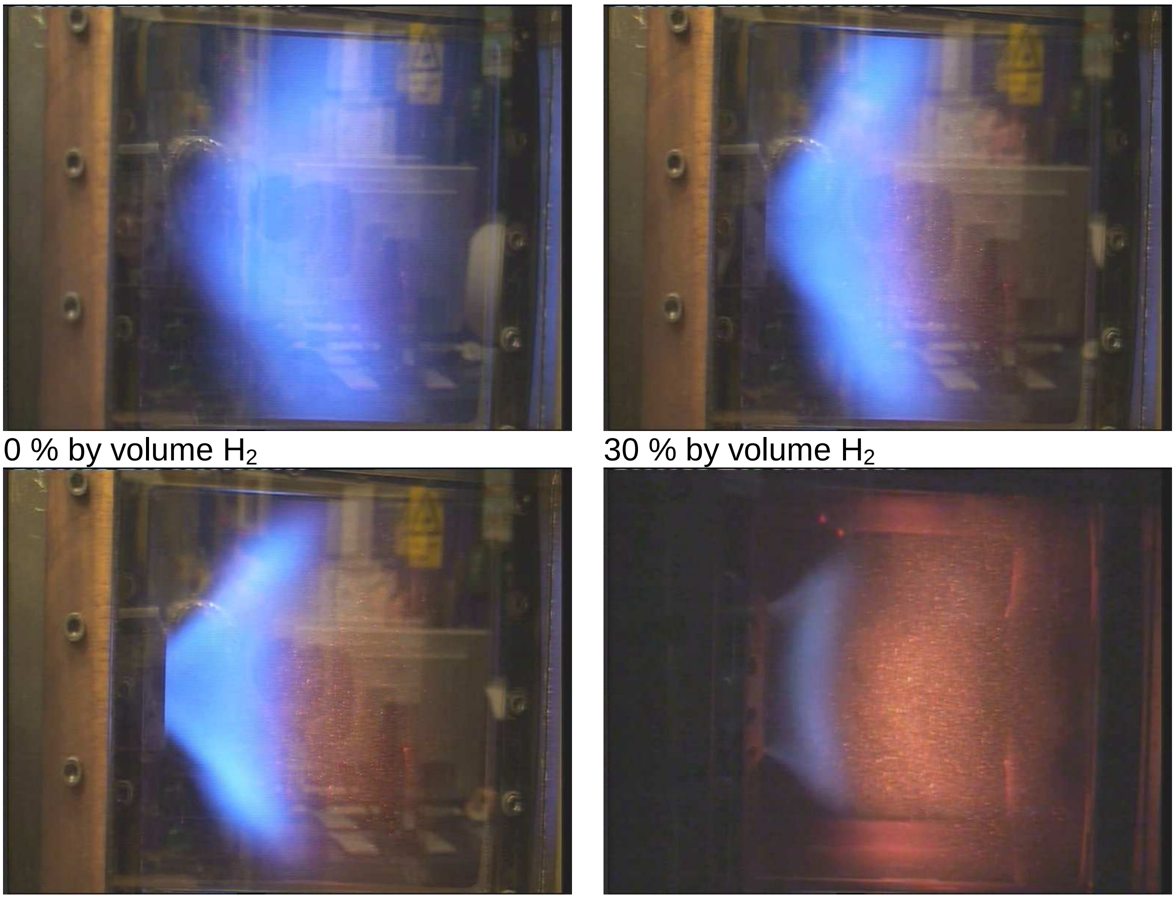


Figure 8. Layout of the atmospheric combustion test rig used for the H_2 enriched measurements.



0 % by volume H_2 | 30 % by volume H_2

60 % by volume H_2 | 100 % by volume H_2

Figure 9. Flame from atmospheric combustion test rig during H_2 enriched measurements.

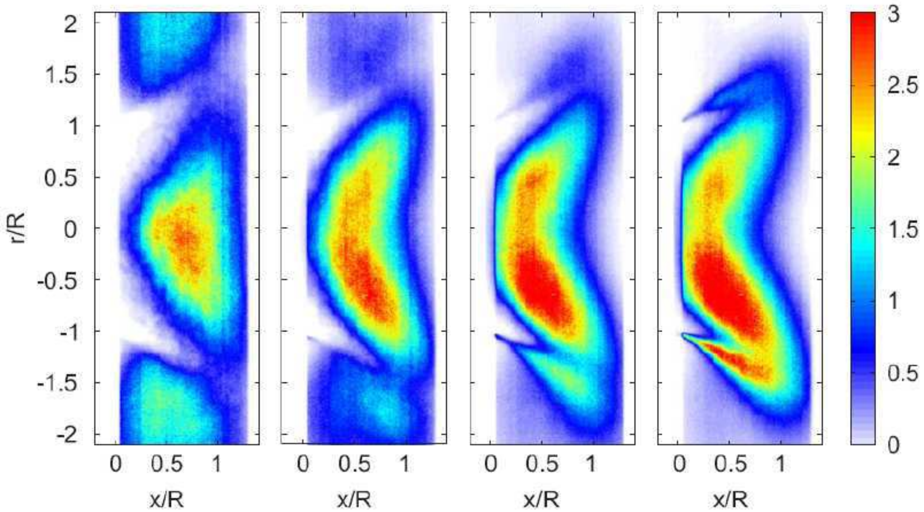


Figure 10. PLIF OH measurement for natural gas with varying hydrogen enrichment (from left hand side 0, 30, 60 and 80 % by volume H_2) in a SGT-800 burner.

5 Fluid dynamic modeling

In this project FOI (Swedish Defense Agency) has performed CFD simulations of the hydrogen enriched atmospheric combustion tests using large eddy simulation with finite rate chemistry.

Fluid dynamics simulation can be performed by a large number of combustion modeling tools available, from relatively cheap and fast-turn-around low order models of limited accuracy (flow networks where only global design information is used) to costly, time consuming highly advanced three dimensional computational fluid dynamics (CFD) where high accuracy is expected. To be commercially efficient, the accuracy must be sufficient to reduce risks and in the same time limit lead time and development budget and therefore the right tools are selected for each task. However, when studying the effect of hydrogen enrichment, the tools in the upper range of the advanced scale are required.

The combustion modeling involves prediction of aero design, CFD, kinetics, thermal acoustics and heat transfer and it is strongly connected to testing for verification purposes, but also to mechanical design, structural analysis and lifing that are dependent on the outcome of the combustion specifics. Combustion tests are of utter importance to verify a new design, where data for main global flow data, wall temperatures, emissions, combustion stability (thermal acoustics, flash back, blow out) may be obtained with good accuracy. However, due to limited optical access and limitations of existing measurement methods, the type of detailed data is limited in tests compared to 3D prediction tools where all data is available. In addition, tests are in general costly and time consuming to set up, while up and running hundreds of test points may be obtained per day.

Therefore the prediction tools complement the tests to reduce the risk of failed tests, reduce the number tests required and hence shorter test periods and to optimize the design before the tests to obtain new goals, that otherwise might be difficult to achieve. However, prediction tools only achieves one test point per simulation and hence the advanced tools that often lasts for days or weeks cannot compete with testing when it comes to the number of test points per day. Therefore simulation tools are aimed for predicting a few selected, representative, test points.

The measured data discussed above has been used for CFD combustion prediction validation. Figure 11 shows the mesh that has been used for the investigation, where the Reynolds Averaged Navier-Stokes simulations (RANS) and the Large Eddy Simulations (LES) have been using a grid size of 8 and 15 million cells respectively. The cells are concentrated in the burners and in the flame region. The locations of the boundary conditions are shown and all air and fuel inlets are positioned at well defined constrictions (perforated plates at air inlet and at the orifices of the fuel inlets respectively).

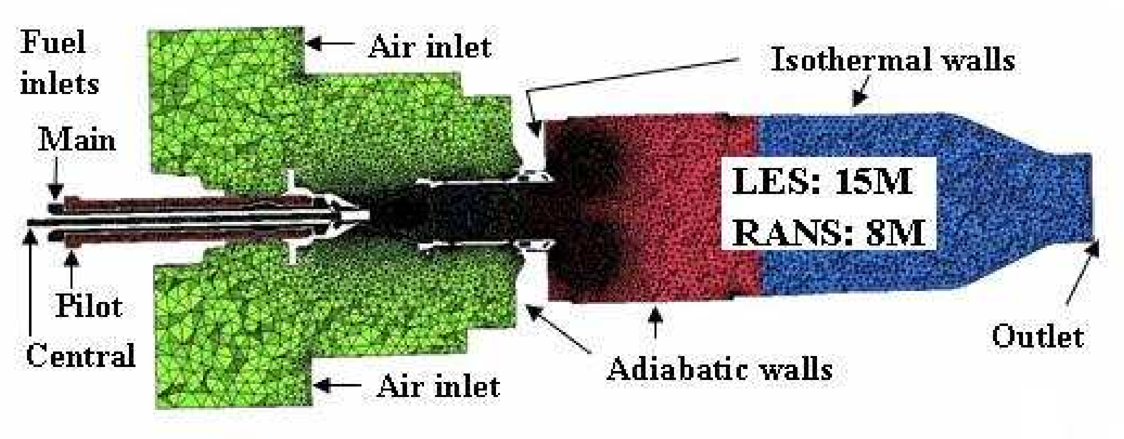


Figure 11. CFD mesh used for RANS and LES.

RANS is performed using ANSYS with SST turbulence model and the burning velocity model (BVM) using Zimont turbulent flame speed closure. LES is performed using the OpenFOAM C++ library with compressible, reactive Navier-Stokes equations using an acoustic Currant number below 1 combined with the Mixed 1-equation sub grid scale model for turbulence, Finite Rate Chemistry (FRC) using Jones and Lindstedt 4-step reduced mechanism for CH_4 and H_2 combustion, Partially Stirred Reactor model for turbulence-chemistry interaction and the Barlow model for thermal radiation. The LES combustion model has been extensively tested quantitatively by FOI for various validation cases. Similar setup has been used as for methane combustion as presented in [7] where more details are shown for these combustion simulations.

Figure 12 shows the typical results for RANS BVM simulations, here evaluated using an axi-symmetric model [9]. The left figures show the temperature field, which defines the un-burnt (blue) and burnt (red) regions with the flame front in between. As clearly seen, the flame length is much shorter when using high amount of hydrogen. However, the flame position at the center line is not much affected by the hydrogen content, as compared to figure 10. The reason is the very high velocity gradient of the averaged velocity field in the flame region, as shown in the right part of figure 12. Even though the flame speed of hydrogen mixtures is much higher than for methane or natural gas mixtures, the center line flame position is not much affected due to this very high velocity gradient. Therefore steady RANS BVM does not seem to be able to predict fuel flexibility influence on flame position for this type of burner and hence more advanced modeling is required.

Figure 13 shows a comparison between the preliminary results of LES FRC for 0 and 60 vol% hydrogen enrichment versus the measurement results in figure 10. The simulations are not yet finished, but instantaneous data are available. Since time averaged results are required for a valid comparison and that preliminary instantaneous results might be different from final time averaged results, this comparison should be interpreted with care. However, the results indicate that LES FRC better may predict the flame position at the center line than RANS BVM.

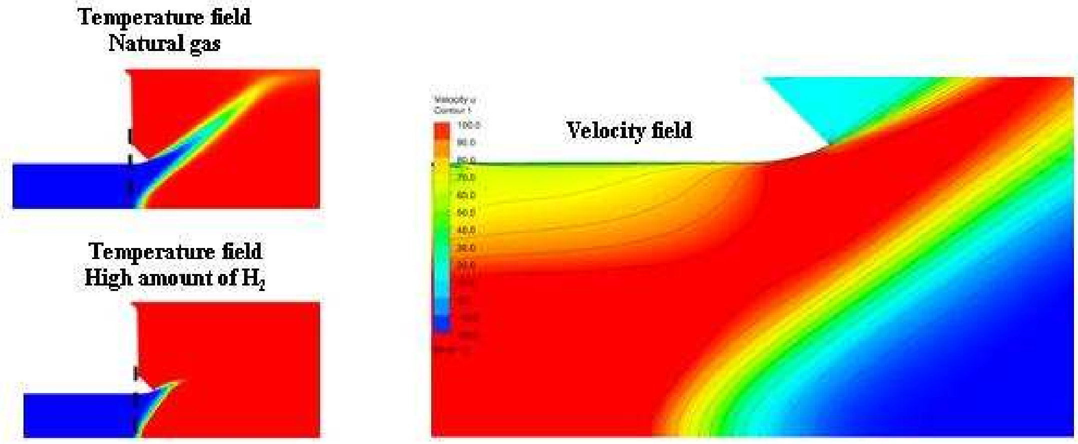


Figure 12. RANS results of temperature field and velocity.

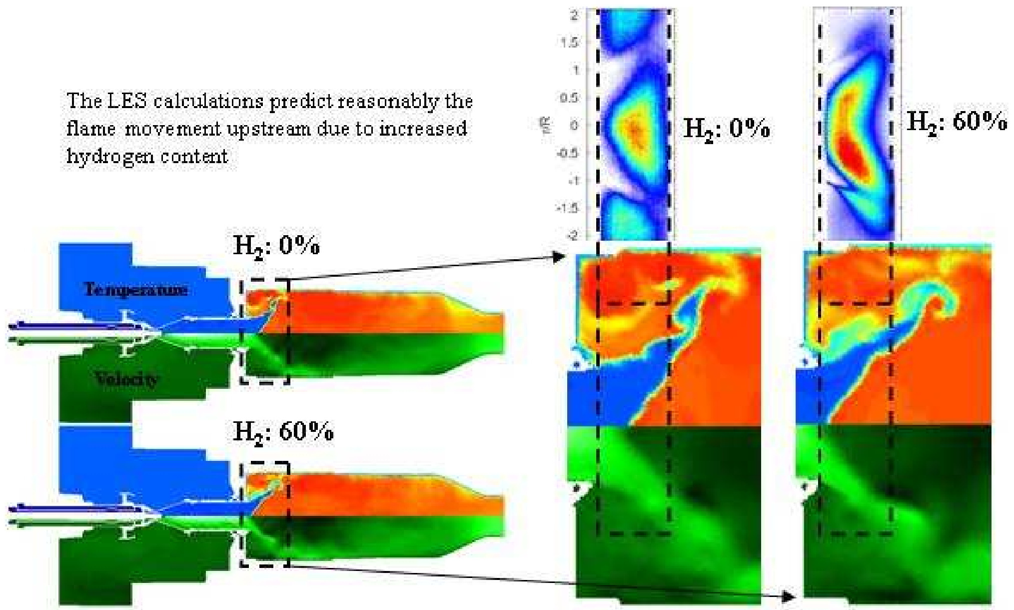


Figure 13. Combustion LES temperature and velocity results with and without hydrogen enrichment as compared to OH measurement.

The next step, after that the time averaged results are confirmed, is to study the effect of hydrogen enrichment at engine conditions using combustion LES. This will require much more computer resources and hence the results of rig conditions have to be thoroughly evaluated first. Both SGT-700 and SGT-800 have been successfully investigated using RANS BVM for natural gas fuels and figure 14 shows an example of the SGT-800 engine using a one burner sector, i.e. 1/30 part of the combustor. As for the rig simulations, the inlets are located at well defined positions (compressor outlet and fuel orifices). The outlet is located after the first row of guide vanes to include the effect of those. Therefore the flow through time is large, since all main air passages upstream the combustor and inside the cooling system, the hood and the combustion chamber are included in the model. In the future, a several burner sector is required to appropriately model the tangential effect and the burner-to-burner interaction. This makes LES of such a system a challenge, and perhaps simplifications might be required to obtain a reasonable size of this model.

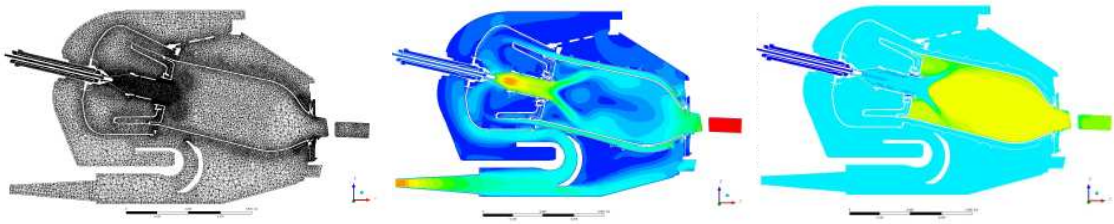


Figure 14. SGT-800 CFD RANS BVM simulation of natural gas. Mesh (left), velocity field (middle) and temperature field (right).

6 Single burner test in engine

In a new approach to fuel flexibility testing, Siemens combines a single burner test with a full scale engine test. The test fuel is separately fed to one burner in a standard gas turbine installation where the other burners use standard fuel from standard fuel system for engine operation [10]. The test fuel to the test burner can be a pure prepared fuel or a mixture of standard natural gas and the test fuel. The procedure described in the reference [10], was also applied during a yet unpublished experiment with ethane (C_2H_6). The test with ethane, also a fuel with quite high flame speed compared to methane, was performed during the summer of 2012 as a sort of pre-test for the hydrogen mixing system and the single burner feed system. Even though ethane behaved very different from both methane and hydrogen and for example needed significant heating to avoid condensation in pipes, it was very valuable for the hydrogen test described below. Several improvements were made to the hydrogen test procedure based on the ethane test. After some initial troubleshooting, it turned out to be fully possible to run the test burner on pure ethane at all reasonable SGT-700 engine load conditions. At extreme test burner combustion settings, it was possible to provoke flame shifting and ways to detect and correct flame shifting were developed and would later be used during the hydrogen test.

6.1 Experimental set up

Testing is performed in Finspong delivery test beds and both the single fuel mixing line and the gas unit 1 (filters, etc) are outdoor installations, see figure 15. The schematic of the single burner feed is illustrated in figure 16. Vaporized LNG, i.e. natural gas, is bled from the main gas supply to the engine and then mixed with hydrogen (or other test fuel) into the experimental burner in the engine. As there are 18 burners in the SGT-700 engine it means that 1/18 of the gas turbine heat demand is supplied to the experimental burner.

The hydrogen flow and the total gas flow to the test burner are measured by Siemens coriolis mass flow meters. Testing was performed in an SGT-700 engine such that all engine equipment and controllers are standard and all test conditions and transients are engine realistic.

Figure 15. Single burner feed unit and Finspong gas turbine delivery test beds.

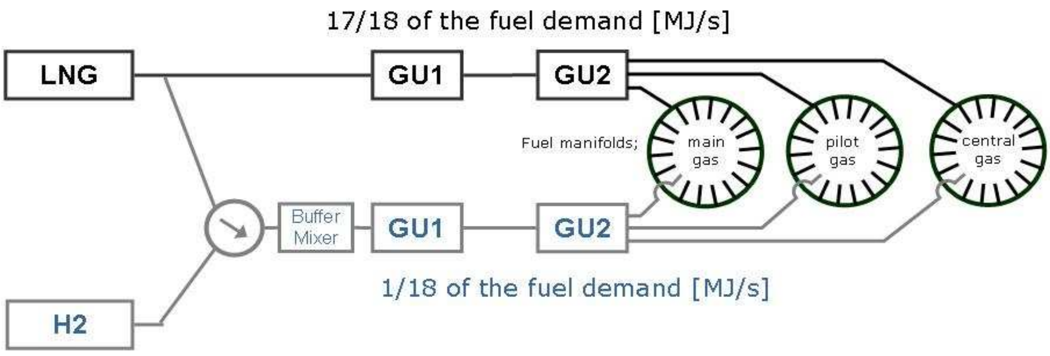


Figure 16. Single burner feed arrangement (GU = gas unit).

6.2 Test burner

During the test, one of the original engine burners is replaced with a special test burner. Two such test burners, configuration number 1 and 2 respectively, were used for tests of hydrogen capability. The burners differs in their fuel distribution configuration and both of them are known from previous testing with heavy hydrocarbon rich fuels [10] as well as from atmospheric combustion testing and also from SGT-800 engine operation (not reported externally). The burners are instrumented with a flashback thermocouple that is mounted in the mixing tube wall as shown in figure 17. One of the test burners also have 20 extra thermocouples mounted in the tip of the burner for temperature monitoring, see figure 18.

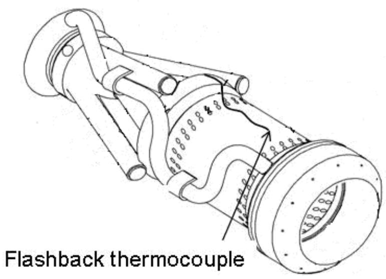


Figure 17. Position of flashback thermocouple in Siemens 3rd generation DLE burner.

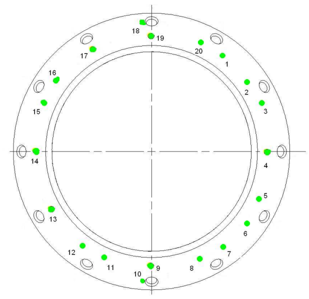


Figure 18. Indications of the thermocouples positions in the burner tip.

6.3 Extra instrumentation on test engine

Also the engine has extra instrumentation during a test with single burner feed as illustrated in figure 19. A boroscope camera is used for visual observation in the combustor at the test burner exit. An emissions measurement probe is located after the turbine, downstream of the test burner.

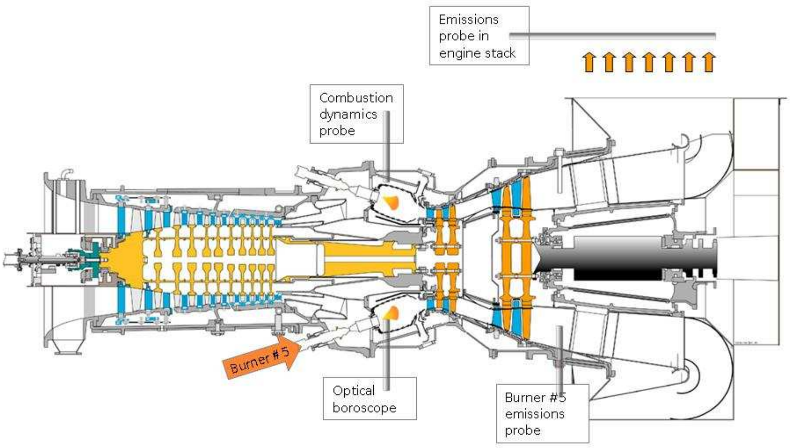


Figure 19. Survey of SGT-700 monitoring equipment during test with single burner feed.

7 Results from single burner feed test

The test was performed between the 18th and 21st of September 2012. During the test the SGT-700 at full load operation delivered about 30 MW electric to the load banks in the test bed.

A test with burner configuration 1 lasted for about two hours and the operation profile is shown in figure 20. The hydrogen mixing into the test burner fuel is started with some initial hydrogen system tests, when the engine load (black line) is around 18 MW load. One hour after start of the test the hydrogen content is about 24 % by volume and the load was increased in two steps to full load. The hydrogen content is reduced when total fuel feed is increased since hydrogen flow is constant. Hydrogen feed was then increased up to 32 % by volume with continued stable combustion. The test is ended with a load reduction using hydrogen rich fuel. The hydrogen flow was reduced before the load reduction as the fuel hydrogen content increases when the total fuel flow drops.

Also shown in figure 20 is the flashback thermocouple reading. Hydrogen can cause the flame to shift position. If it moves significantly upstream into the burner, i.e. flashback, this temperature would immediately increase. The burner temperature at stable operation corresponds to the mixing temperature of air and fuel in the gas turbine. As gas turbine load increases the combustion air temperature increases, which can be seen in figure 20. During the test no flashback tendency was observed.

Figure 21 shows a test with burner configuration 2 where the compressor inlet temperature was controlled with electrical heaters. For constant electrical load a change in compressor inlet temperature corresponds to a change in relative load. Higher compressor inlet temperature means a higher relative load. Hydrogen was fed to a targeted concentration of about 30 vol% during the higher inlet temperature. Hydrogen feeding was lowered before the compressor inlet temperature was changed. During the last part of the test even higher hydrogen levels were tested, up to 40 % by volume. This test shows that a small load reduction allows higher hydrogen content to be used.

In all test the increase in hydrogen content was stopped when indications of flame shifting was seen. For burner configuration 1 this was observed on the flashback thermocouple for the main flame. For burner configuration 2 the indication of flame shifting took place in the pilot noted by the extra instrumented thermocouples as well as visual observation in boroscope camera.

Gas samples were also taken during the test. See Appendix 1 for analysis of a sample with close to peak concentration of hydrogen. The time for sampling is marked with a vertical line in figure 21. The analysis showed slightly lower hydrogen concentration, 34 % by volume, than expected, 38 % by volume, from the mass flow meter readings. Since hydrogen is very diffusive this error can be associated with the sampling procedure but also there were some instabilities in the hydrogen feeding system.

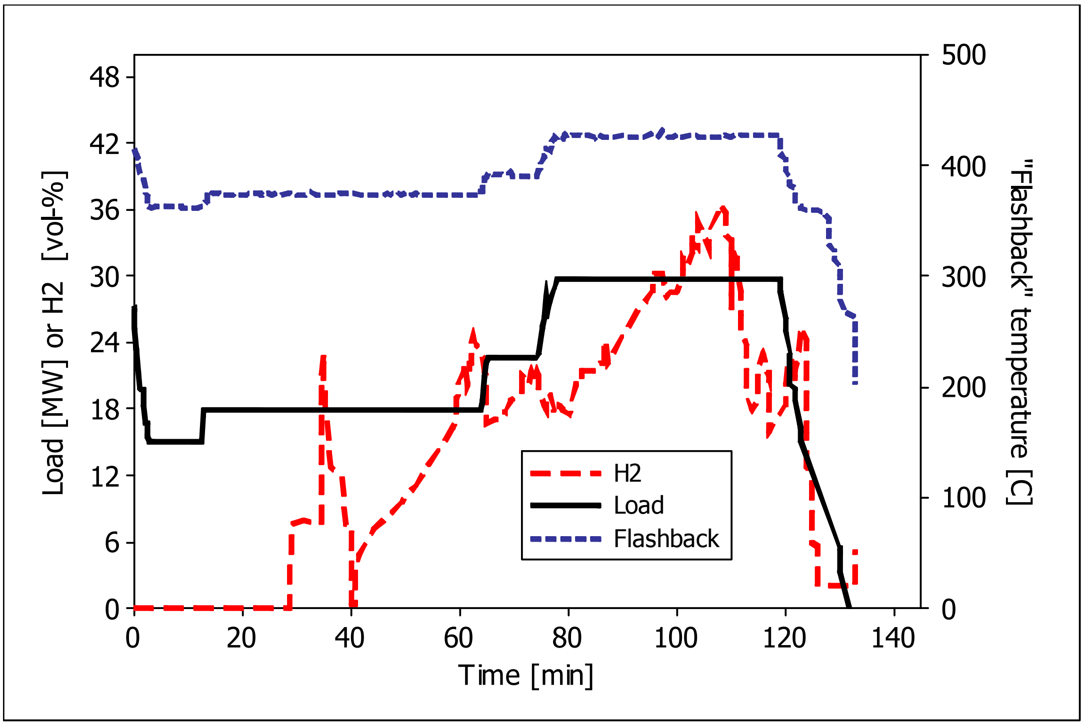


Figure 20. Stable operation at various loads with hydrogen feeding.

Through the boroscope probe the flame was monitored as the hydrogen content in the fuel gas was increased. In all pictures shown in figure 22 the burner configuration 1 was operated with a pilot to fuel ratio of 6%, starting with pure natural gas and increasing hydrogen to 12, 20, 27 and 32 % by volume respectively. The other 17 burners in the annular combustor were operated at the stable pilot to fuel ratio of 10%. During natural gas operation yellow flames, undesired from NOx formation point of view, are seen. There are no clear pilot flames but rather the natural gas is “swept away” and burns in a recirculation point at an intermediate burner position. As hydrogen is fed into the test burner the pilot flames appear and the fuel burns closer to the fuel exit ports. Increasing hydrogen content from 12 % by volume up to the 32 % by volume does not change the flame position but the light intensity increases and the flames appear whiter.

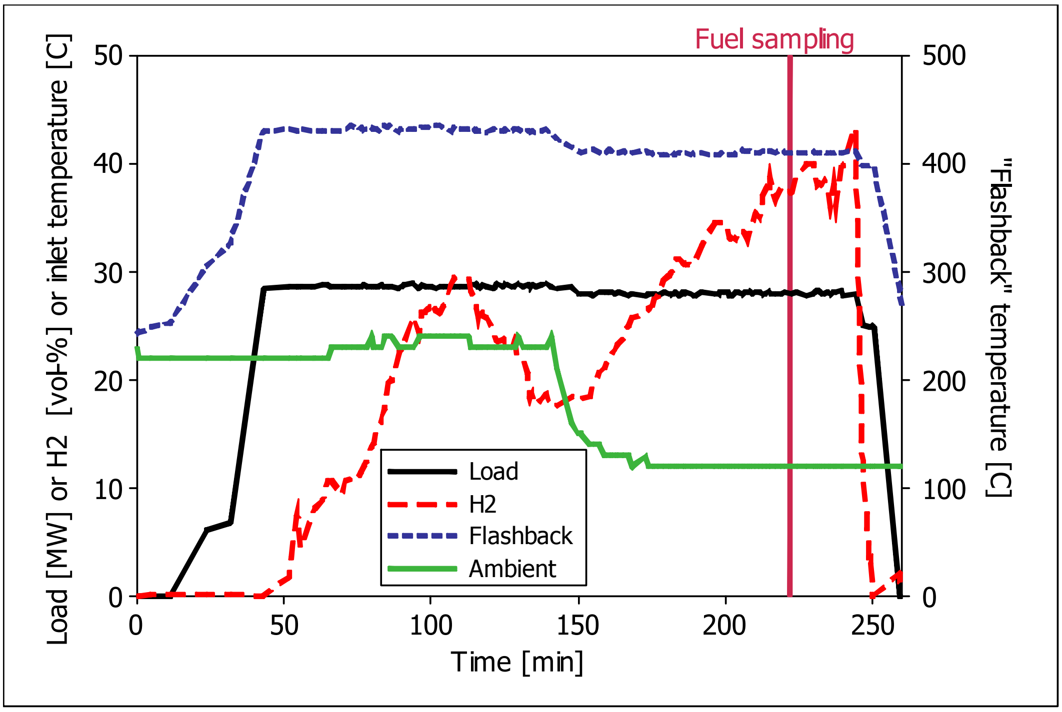
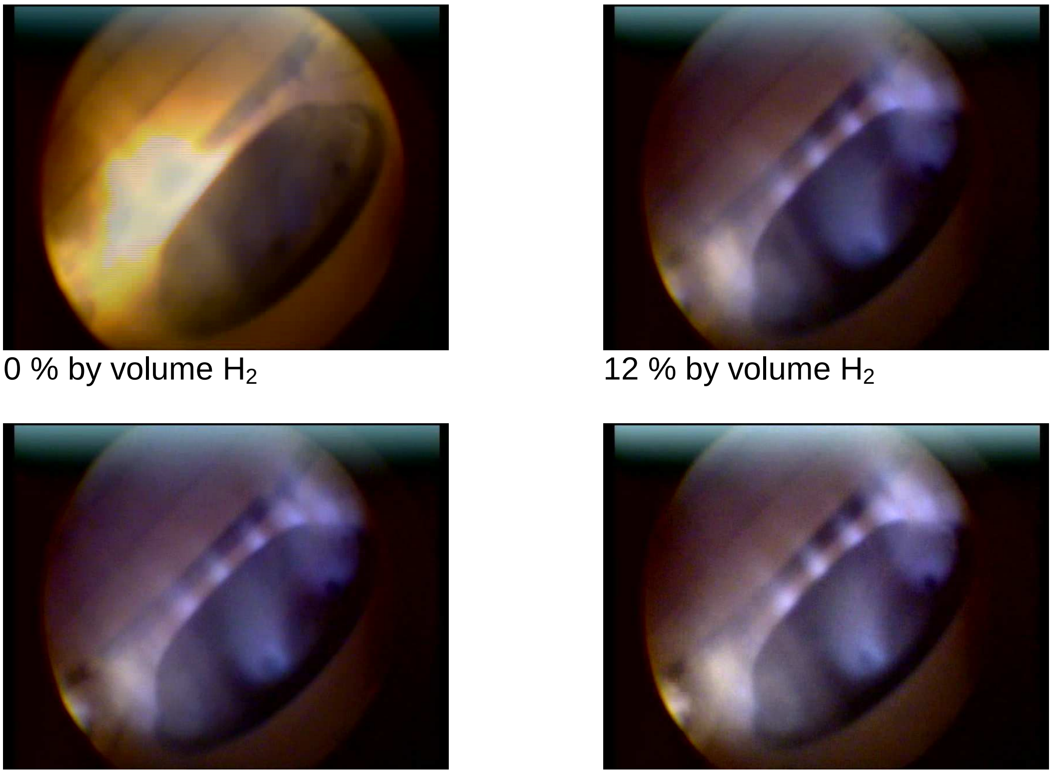


Figure 21. Stable operation at two different ambient temperatures. Fuel sample taken at around 220 minutes indicated by red arrow.



0 % by volume H_2 | 12 % by volume H_2

20 % by volume H_2 | 32 % by volume H_2

Figure 22. View over test burner configuration 1 through boroscope camera during test with increasing content of hydrogen in the natural gas.

The emissions of NOx measured after the turbine, downstream the test burner, are shown in figure 23 versus hydrogen content. The NOx emissions are normalized to a reference case of operation on pure natural gas. For burner configuration 1 there is no influence of the changing fuel composition. For burner configuration 2 there is a small increase in NOx with increasing hydrogen content. For burner configuration 1 this is in agreement with the visual observation that flame position is not changing and therefore combustion situation is not affected. For instance a hot spot would lead to increase in NOx production.

Emissions of CO were also measured and the values were found to be low, between 2 to 10 ppm, for both natural gas and hydrogen enriched operation at all times. Combustion dynamics monitored in the burner as well as in the combustor do not show any change in peak frequency or dynamic pressure in the low frequency interval (0-200 Hz) or in the medium frequency interval (200-600 Hz). Since the SGT-700 combustor is film cooled there are no high frequency combustion dynamics (above 600 Hz). Rather the hydrogen introduction seems to have a stabilizing effect on the flames.

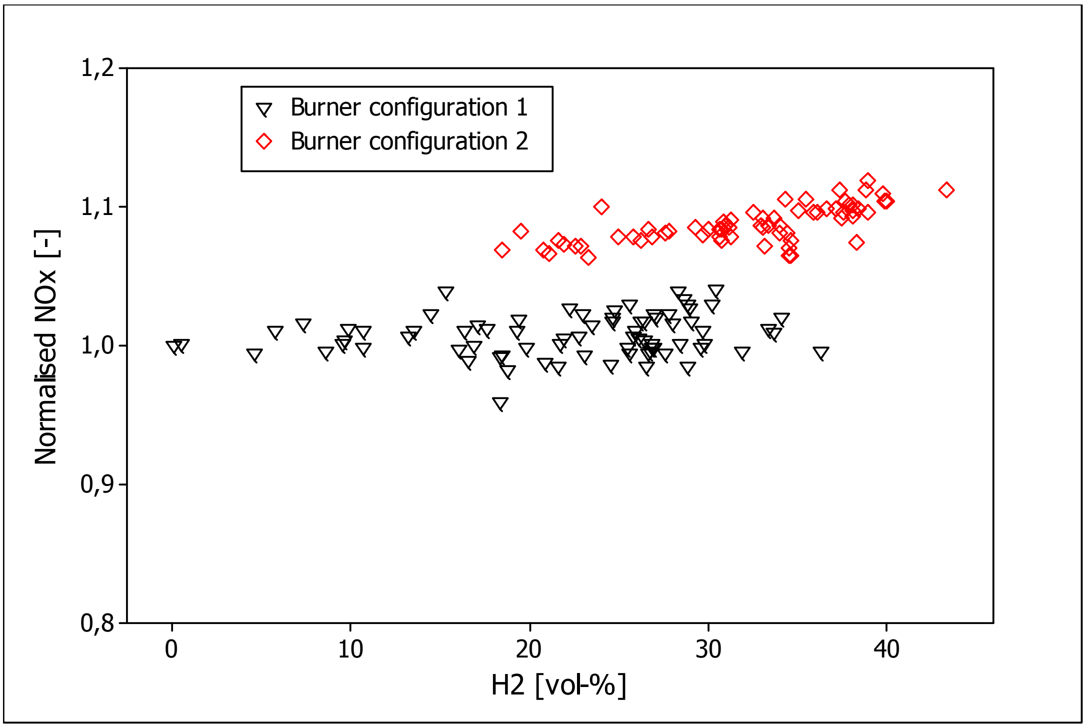


Figure 23. Normalized NOx emissions versus hydrogen content in the test burner.

The temperatures measured in the tip of the burner are shown in figure 24. These temperature readings from SGT-700 with and without hydrogen mixing can be compared with earlier readings from same burner on natural gas but in a SGT-800. The latter is then defining a reference condition used for normalization in the figure. If the temperature reading in the SGT-700 coincides with the SGT-800 engine, the normalized temperature is 1. As seen, the normalized temperature for operation on natural gas (black crosses) deviates up to 15% between the engines. Introducing hydrogen into the burner (red squares) has no or little influence on the temperature distribution. A small increase in some positions is seen which is consistent with the visual observations in figure 22. It is therefore concluded that the burner co-fired with this concentration of hydrogen is operated within an acceptable range for burner tip life.

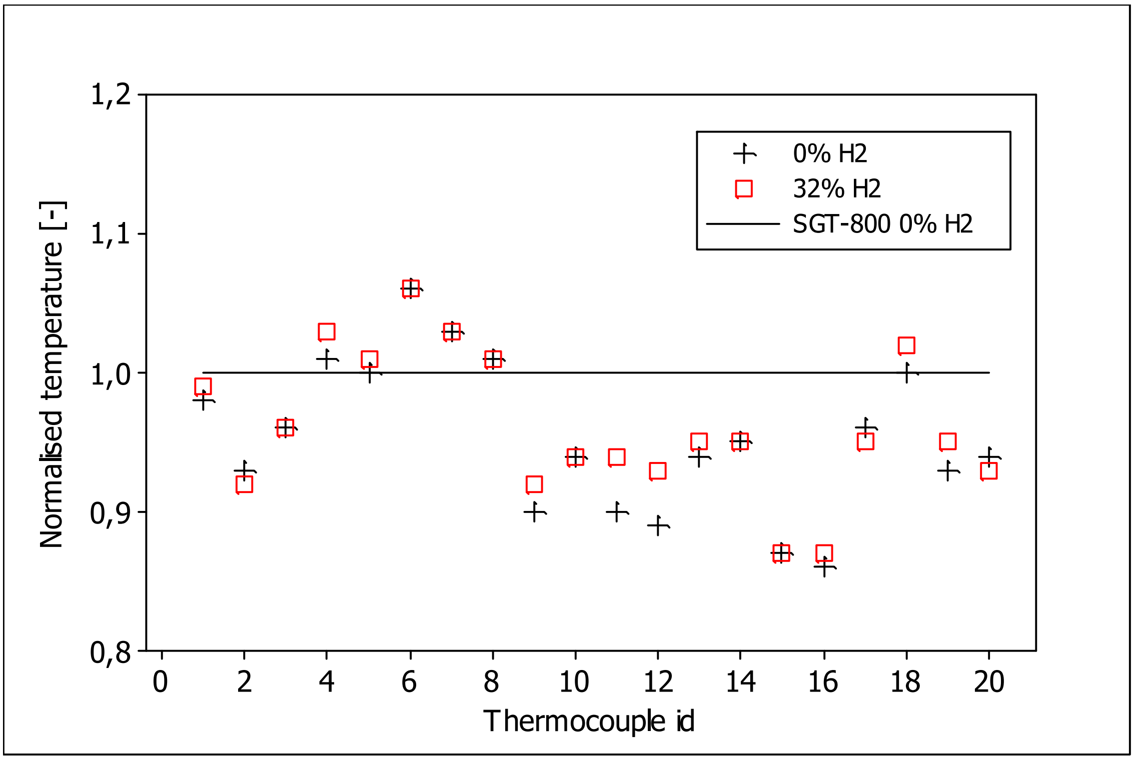


Figure 24. Normalized temperatures in burner tip during operation on natural gas in the single burner feed in SGT-700 with and without hydrogen. Reference case is natural gas operation in SGT-800.

8 Conclusions

Stable operation at near 40 % by volume H_2 has been demonstrated in a Siemens gas turbine SGT-700. For the two burner configurations tested some limitations in hydrogen capability was found. In one the pilot seems to set limits and in the other the main flame is limiting. This gave valuable information and understanding for continued development efforts.

The stability of the hydrogen feeding system was not as accurate as desired, especially at higher hydrogen contents and it is concluded that it needs improvement. This inaccuracy was however not of such significance that main results and conclusions are compromised.

Based on this test the accepted level of hydrogen in the SGT-700 and SGT-800 was increased to 15 % by volume, well above the proposed level of 10 % H_2 by volume in the European natural gas net.

9 Literature

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Appendix 1: Fuel Analysis during test

Component	Chemical formula	Conc. (mol%)	U_{rel} [1,2] (%)	Component	Chemical formula	Conc. (mol%)	U_{rel} (%)
Helium	He			Methylcyclopentane	C_6H_{12}	0.002	< 15
Hydrogen	H_2	34.24*	< 3	2,2,3-Trimetylbutane	C_7H_{16}		
Oxygen	O_2			Benzene	C_6H_6	< 0.001	-
Nitrogen	N_2	0.151	< 11	Cyclohexane	C_6H_{12}	0.001	< 15
Carbon dioxide	CO_2			2-Methylhexane	C_7H_{16}		
Methane	CH_4	61.66	< 1	2,3-Dimethylpentane	C_7H_{16}		
Ethane	C_2H_6	3.036	< 2	1,1-Dimethylcyclopentane	C_7H_{14}		
Propane	C_3H_8	0.628	< 2	3-Methylhexane	C_7H_{16}		
i-Butane	i-C_4H_{10}	0.158	< 12	cis 1,3-Dimethylcyclopentane	C_7H_{14}		
n-Butane	n-C_4H_{10}	0.085	< 12	trans 1,2-Dimethylcyclopentane	C_7H_{14}		
2,2-Dimethylpropane	C_5H_{12}	0.001	< 15	2,2,4-trimethylpentane	C_8H_{18}		
i-Pentane	C_5H_{12}	0.019	< 15	n-Heptan	C_7H_{16}		
n-Pentane	C_5H_{12}	0.010	< 12	Methylcyclohexane	C_7H_{14}	< 0.001	-
2,2-Dimethylbutane	C_6H_{14}	< 0.001	-	2,4-Dimethylhexane	C_8H_{18}		
Cyclopentane	C_5H_{10}	< 0.001	-	Toluene	C_7H_8		
2-Methylpentane	C_6H_{14}	0.002	< 15	1,2,3-Trimethylcyclopentane	C_8H_{16}		
3-Methylpentane	C_6H_{14}	0.001	< 15	1,1-Dimethylcyclohexane	C_8H_{16}		
n-Hexane	C_6H_{14}	0.001	< 12	n-Octane	C_8H_{18}		
2,2-Dimethylpentane	C_7H_{16}			n-Nonane	C_9H_{20}		

*Results of hydrocarbons <0.001mol% is beyond the scope of the accreditation

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