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SGT-750 FUEL FLEXIBILITY, ENGINE AND RIG TESTS

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Abstract

This paper will discuss fuel gas flexibility and its importance for operation in the oil and gas industry. Environmental awareness and related regulations prohibit or limits venting or flaring certain gases. Maintaining mandated low emission levels over fuel property changes requires increased flexibility of the turbine combustion systems.

The paper will also describe the fuel flexibility tests performed for SGT-750 gas turbine and how variations in Wobbe Index are handled by the control system. The SGT-750 gas turbine has a control algorithm using the standard gas turbine parameters and doesn't need the use of external Wobbe Index metering system.

The SGT-750 is a high performance twin shaft gas turbine rated at 41 MW with 41,6% simple cycle efficiency and is designed for both mechanical drive and power generation applications. The gas turbine has a DLE combustion system designed to cope with variations in fuel composition while keeping very low NOx emissions.

In the paper different tests will be discussed. In a single burner high pressure test rig a full fuel flexibility test has been conducted. The tests were done for both inert and reactive gas blends. High concentrations of inert gases, nitrogen and carbon dioxide, were tested at simulated extreme cold conditions (down to -60°C) at full and part loads. Reactive gases such as ethane, propane, butane, hydrogen and also syngas blends were successfully tested.

At the Siemens gas turbine test facility in Finspong several engine tests for the whole load range with up to 50% nitrogen and 40% carbon dioxide were performed.

During these tests the limit for the inert fractions was the delivery system and not the combustion system. These tests will be described in the paper together with the control philosophy.

1 INTRODUCTION

1.1 General design

The SGT-750 is a twin shaft gas turbine with a free power turbine, see Figure 1.1. It can be used both for power generation and as a mechanical drive, [1].This gas turbine attains an efficiency level of 41,6 % as and has a capacity of 41,MW (shaft).

The complete gas turbine unit is mounted on a single base frame in which the lube oil tank is integrated. All the auxiliary systems such as start motor and electrically driven back-up systems are mounted on the base frame.

The compressor has 13 stages and a pressure ratio of 24:1. Two variable guide vane rows and three compressor bleeds located after stages 3, 6 and 9 which are used for start-up and part load operation. The gas generator rotor is electron beam welded. After welding the compressor rotor forms a solid rotor body which ensures a very stable operation, this manufacturing technology has been used on Siemens gas turbines for a long time.

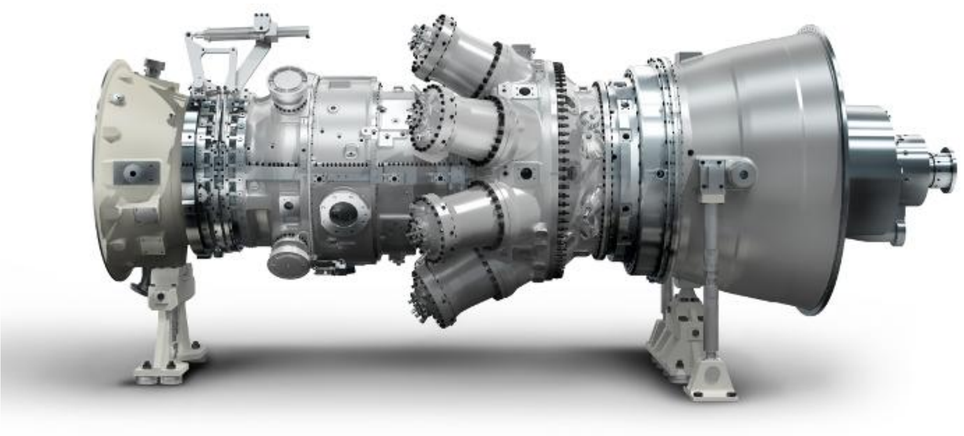

Figure 1.1 The SGT-750 twin shaft 41 MW engine.

The combustion system is a can combustor system with 8 cans. The cans are of a double-skin convective cooled design. The fourth generation DLE (Dry Low Emissions) burners offer dual fuel on-line switchover capability, high turn down ratio, and exceptionally low NOx emissions without any need tor staging or seasonal mapping, see Figure 1.2.

The turbine section of the SGT-750 consists of the two-stage air-cooled compressor turbine and the two-stage uncooled power turbine.

The stage 1 vane and blade are film cooled with compressor discharge air. These blades and vanes have a thermal barrier coating for reduced cooling air consumption. The stage 2 vane and blade are convection cooled with cooling air from compressor stage 9. The turbine discs are bolted to the rotor with tie-bolts.

The free power turbine can be used for fixed speed power generation at a nominal speed of 6100 rpm or used as a variable speed mechanical driver with a speed range of 50-105% of the nominal speed. Blade 3 and 4 are shrouded for dynamic damping.

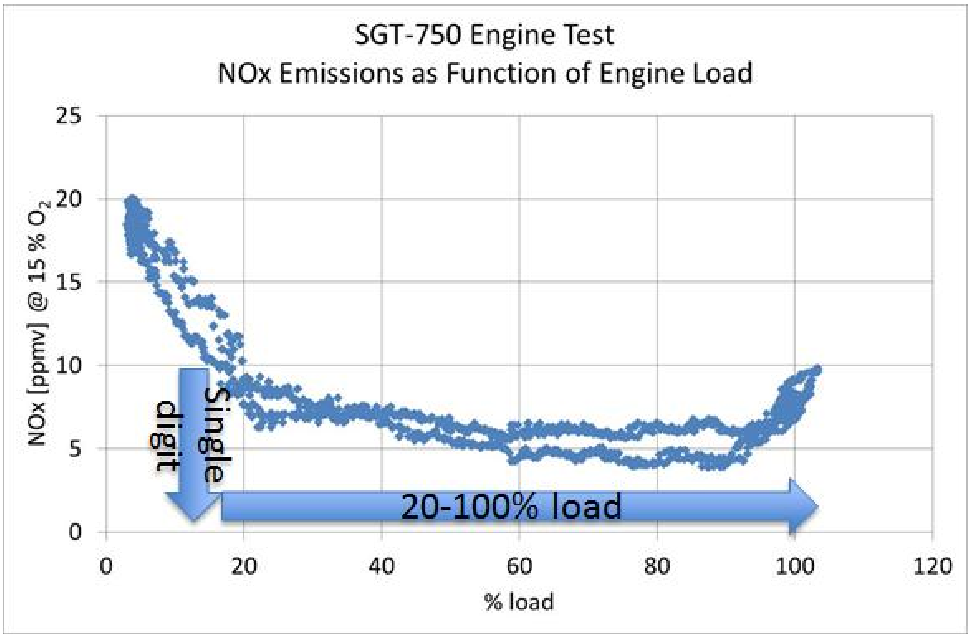

Figure 1.2 SGT-750, emissions. Standard natural gas fuel operation.

1.2 The combustion system

The SGT-750 combustion system is based on the experience from Siemens gas turbine fleet. The system consists of eight burners, cans and transition ducts, see Figure 1.3. The air flow from the compressor diffuser enters the central casing plenum where it flows between the radial struts and the transition ducts entering the can cooling channels. Downstream the cooling channel, the air enters the burner. The burner consists of a main swirler with a split plate that separates the main1 and main2 channels, a central pilot and a central combustor, the RPL (Rich Pilot Lean). The main flame is stabilized in the quarl by a strong central recirculation zone as shown in Figure 1.3. A portion of the air is bypassing the burner to achieve a desired flame temperature. The bypassed air is also used for impingement-effusion cooling of the transition duct.

1.3 Control system and Adaptive Wobbe Algorithm

The SGT-750 control system handles the gas turbine, auxiliaries and driven equipment, the control system is built on a standard microcomputer based system. In the control system an automatic fuel characteristics adaptation algorithm has been implemented to the control system for adjustment of fuel dependent limiters when the Wobbe Index of the gas changed. The algorithm is based on engine characteristics and the standard parameters (signals) measured on the gas turbine such as fuel consumption, inlet conditions, conditions after the compressor and outlet conditions. The system does not require any calorimeter or gas chromatograph for measuring the gas properties. This made it possible to implement different combustion settings as a function of Wobbe Index as engine response to changes is faster than standard measurement systems. Resulting Wobbe index from this algorithm is shown in some figures in section 6.

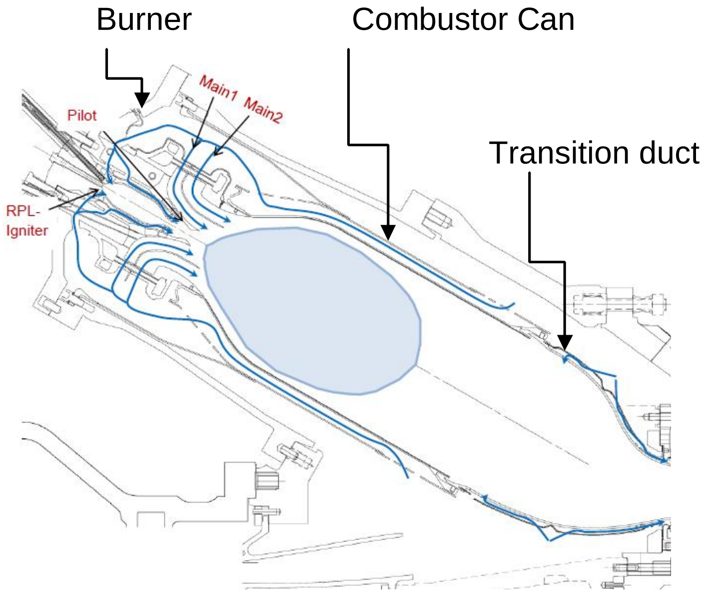

Figure 1.3 SGT-750 combustion system.

2 GAS TURBINE COMBUSTION TESTING

Fuel flexibility is becoming increasingly important on the market and consequently there has been a strong push for verifying the fuel flexibility of the SGT-750 engine and its combustion system. The SGT-600/700/800 burner type has been extensively tested on a variety of fuels, [2-6] but the SGT-750 burner fuel flexibility has up to now only been fully tested in single burner rigs, [7].

Lean gases, i.e. gases containing high amounts of nitrogen or carbon dioxide are interesting since the operator does not need to clean the fuel up and the ability to burn these types of gases means less equipment and lower cost. Such gases are abundant in the production of LNG and other natural gas processing applications. Gas turbines for power generation or mechanical drive are very attractive from a number of perspectives in these types of applications, especially if lean “waste fuels” can be used efficiently. It can also be very valuable, in the same application, to be able to utilize other surplus gases (e.g. heavy hydrocarbons).

Typical applications where fuel flexibility is needed are situated globally at ambient conditions ranging from -60°C to +50°C. Operation, including starts, of the SGT-750 engine with high and varying amounts of N_2 and CO_2 in the fuel should be verified. It is not possible to conduct this test at one single location and therefore the following test campaigns were defined:

- Ignition and start-up of the SGT-750 at arctic conditions, a novel method for atmospheric combustion testing should be developed to verify reliable ignition in a test at true arctic conditions (-60°C) testing in Siemens Atmospheric Combustion Rig in Finspong, Sweden.

- Verified operation of the complete combustion system in a high pressure combustion test rig at authentic arctic compressor discharge temperature and pressure. Natural gas fuel with different concentrations of N_2 and CO_2. Testing was done at DLR, Cologne, Germany.
- Heavier hydrocarbons, hydrogen and syngas blended with natural gas were also explored, as DLR could offer tests on these gases within the allocated test period.
- Engine operation, including starts, of the SGT-750 engine with high and varying amounts of N_2 and CO_2 in the fuel was verified at near ISO condition. Testing was done at Siemens test facility in Finspong, Sweden.

3 IGNITION TESTS IN ATMOSPHERIC RIG AT ARCTIC CONDITIONS

During start-up of a gas turbine the compressor runs at low speed and low pressure is built up. Ignition tests can therefore be done at atmospheric conditions. Consequently, ignition testing is commonly done in designated atmospheric combustion test rigs. Siemens Industrial Turbomachinery have a flexible atmospheric combustion test rig available in Finspong, Sweden and this was used for an ignition test series at extremely cold ambient conditions.

A full scale SGT-750 standard combustion system including one burner can and transition duct was used. In order to provide the combustion air to the test rig with the required O_2/N_2 content and temperature, a special air supply unit incorporating liquid air storage, steam driven liquid air evaporator and a flow- and temperature- control station was assembled. This was prepared by the gas supply company, where there is unique experience on the use of liquid air.

The test was performed for a variety of air flow rates in the temperature range from -60 to -30°C. The start settings of fuel flow rates to the igniter and main burner was varied to find the optimal ignition conditions. Tests were done with natural gas with different blends of nitrogen and carbon dioxide. The SGT-750 combustion system could successfully be ignited at conditions identical to engine identical start up conditions, at an air temperature down to -60°C. Pure natural gas and natural gas diluted with up to 55 vol% N_2 and 30 vol% CO_2 respectively were ignited successfully in the test setup, giving confidence in the true arctic capabilities.

4 LEAN GAS FUELS TEST AT ARCTIC CONDITIONS IN SINGLE BURNER HIGH PRESSURE RIG

It is not possible to perform a full engine test at arctic conditions (-60°C) since there is yet no SGT-750 installed at such location. Therefore the fuel flexibility test campaign with inert components in natural gas was performed in the single burner high pressure test facility at DLR (German Aerospace Center) in Cologne, Germany.

The tests in HPCR in DLR allowed validation of the standard SGT-750 combustion system for the complete engine load range at cold climate. CO_2 and N_2 mixtures with natural gas was used. The engine test experience on gas fuel mixtures containing large fractions of inert gases indicated that the most challenging operating conditions are low firing temperatures and low combustor inlet air temperatures. The HPCR testing therefore focused on low engine load conditions at extremely cold conditions in order to validate the SGT-750 robustness to flame extinction and combustion dynamics.

The test campaign planning was influenced by a specific project demand which required combustion system operation with mixture of natural gas with 20vol% of CO_2 at equivalent cold ambient conditions (-60°C). The results with 20vol% of CO_2 in natural gas are summarized in Figure 4.1 were the NOx emissions, the combustion dynamics and the combustor inlet air temperature are shown.

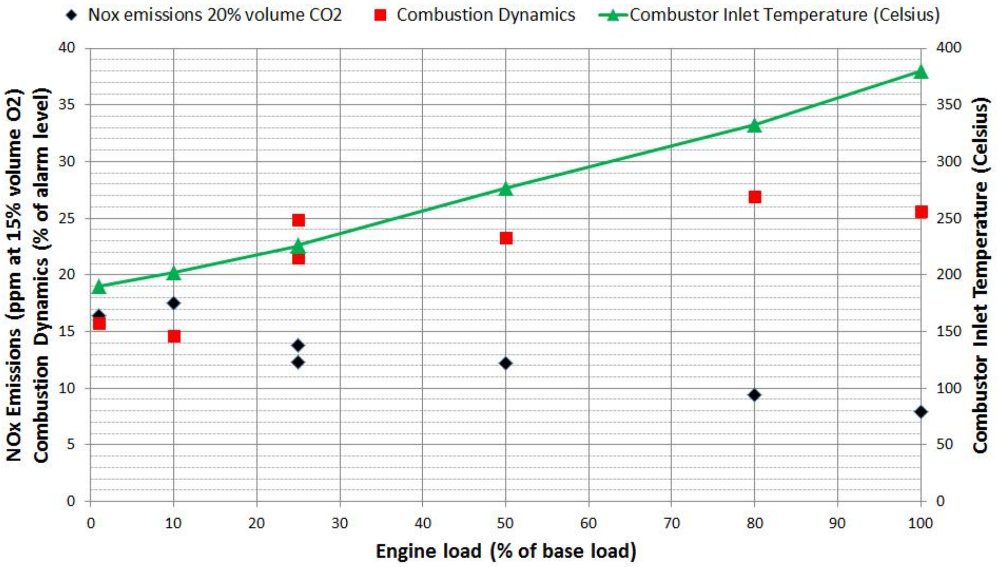

Figure 4.1 Test results on HPCR with gas fuel mixtures containing 20vol% CO_2.

At the lowest engine load the combustor inlet air temperature is around 200°C, this is the most critical point for starting on lean fuels. The combustion system showed capabilities for low NOx emissions combined with low combustion dynamics. The test points at higher load showed that it was possible to reach NOx emissions below 10 ppmv at 15% O_2 with low combustion dynamics.

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Table 4.1 Test results in HPCR at low load cold climate conditions using high concentrations of N_2 and CO_2 in gas fuel.

	5% load	25% load	5% load	25% load
CO_2 (vol%)	37	40	0	0
N_2 (vol%)	0	0	42	53
NO_x (ppm at 15% O_2)	8.4	5.3	10.9	3.7

In order to test the operability limits for the SGT-750 combustion system with inert gas mixtures, higher levels of CO_2 and N_2 were tested at equivalent operating conditions corresponding to 5% and 25% of engine load at -60°C ambient temperature. The results in Table 4.1 show that 42vol% N_2 and 37vol% CO_2 was used at the most difficult operating points (5% load; -60°C ambient temperature) maintaining low NOx emissions.

The single burner test campaign in DLR confirmed the high capability of the SGT-750 burner to operate reliably with high concentrations of inert gases in natural gas even at conditions equivalent to -60°C ambient temperature

5 SINGLE BURNER HIGH PRESSURE RIG TESTS WITH HEAVY HYDRO CARBONS AND HYDROGEN

After the lean gas test at DLR a second test of the fuel flexibility of the SGT-750 burner with highly reactive fuels was performed. This campaign was used to understand the SGT-750 burner capability to burn mixtures of ethane, propane, butane, hydrogen and a mixture of hydrogen combined with carbon monoxide.

For the inert gas mixtures with natural gas as discussed in Chapter 3, cold climate was used as reference testing condition, but for highly reactive fuels the most difficult phenomena occur at higher preheat and firing temperatures which induce higher risks for flashback and increased NO_x emissions. For highly reactive fuels the tests were performed at conditions corresponding to the engine full load at ISO-range temperatures (15°C).

The test results obtained by using ethane, propane and butane mixtures are summarized in Table 5.1. The limiting factor for the concentration levels tested for ethane, propane and butane was not defined by combustion issues but was related to the maximum mass flow that was achievable by the DLR test facility at the time of testing.

Table 5.1 Test results in HPCR at full load conditions using gas fuel mixtures with ethane, propane and butane.

	High C_2 test	High C_3 test	High C_4 test
C_2 (vol%)	35.6	5.0	5.9
C_3 (vol%)	0.0	26.4	0.0
C_4 (vol%)	0.0	0.0	13.4
NO_x (ppm at 15% O_2)	8.2	8.9	9.4

It is expected that the SGT-750 burner is capable to achieve stable combustion and low NO_x emissions even at higher concentrations than is shown here.

The combustion system was also tested on gas mixtures of CO and H_2, which combines the low auto-ignition energy of carbon monoxide with the high flame speed of hydrogen (see Figure 5.1). 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_x emissions below 15ppmv at 15% O_2 for loads above 50% of base load and single digit NO_x for loads above 80%. The concentration of hydrogen was reduced while increasing engine load in order to maintain NO_x emissions around 10 ppmv.

Figure 5.2 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_x at15% O_2 while having up to 25vol% of hydrogen in natural gas fuel. The NO_x emissions could be tuned below 20 ppmv at15% O_2 for hydrogen concentrations up to 35vol%. The NO_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_x below 25 ppmv at15% O_2 for hydrogen concentrations above 37vol%.

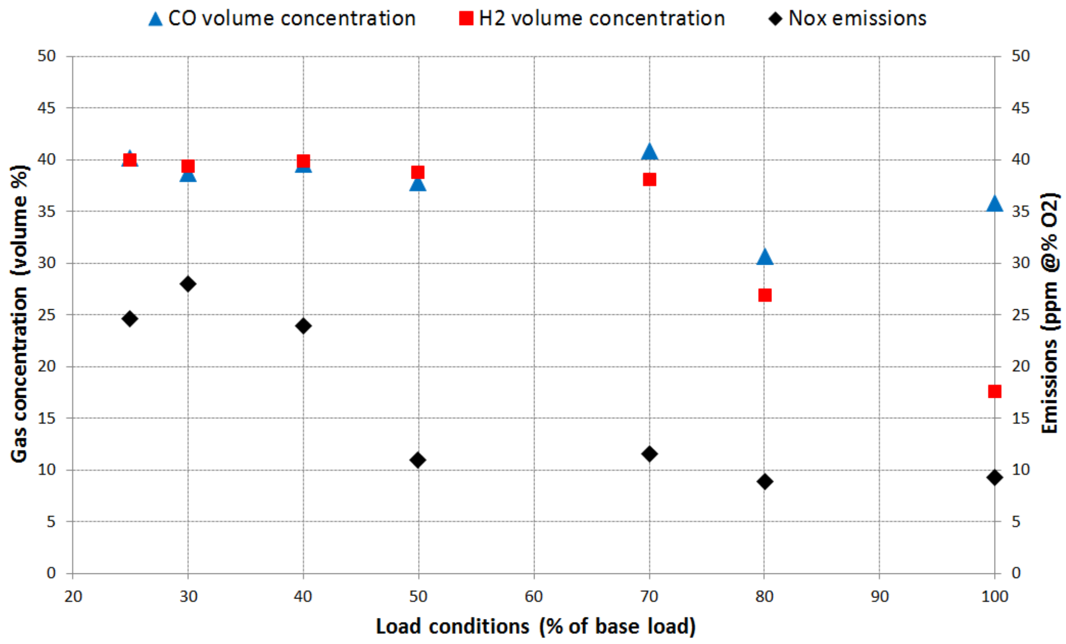

Figure 5.1 Test results in HPCR using gas fuel mixtures containing combined mixtures of CO and H_2.

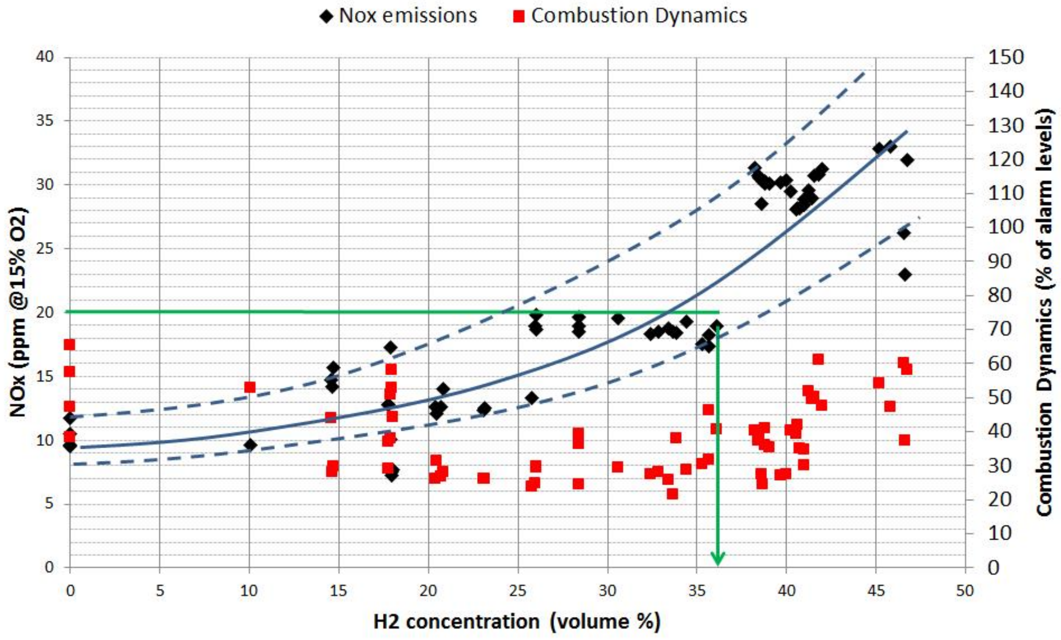

Figure 5.2 Test results in HPCR at full load conditions with increasing concentrations of hydrogen in the gas fuel.

The low frequency combustion dynamics were low for all the hydrogen gas mixtures tested. When comparing with pure natural gas levels it is not possible to see a significant increase of combustion dynamics as shown in Figure 5.2. The test results shown in figure 5.2 also contain test points taken just after the hydrogen concentration was increased and those show higher NO_x emissions. At hydrogen concentrations corresponding to 18vol% and 47vol% the fuel splits were altered to explore the NO_x and combustion dynamics response showing the low NO_x capability also at high hydrogen concentrations.

6 GAS TURBINE TEST WITH LEAN GAS FUELS

6.1 Operation with high content of CO_2 and N_2

The SGT-750 gas turbine was tested with high inert (N_2, CO_2) fuels during a three week test campaign at Siemens gas turbine test facility in Finspong, Sweden. The aim was both to investigate the behaviour during steady state operation, but also to see the responses to variations in fuel composition and to transients in engine operation. Ignition and start tests were also performed during the campaign (see section 6.2).

The test engine was of standard design, but with some extra instrumentation, e.g. thermocouples in the combustor. No modification was done to the combustion system hardware for the test. The gas supply pressure upstream the fuel control valves was kept at a similar level during the N_2 test as for natural gas operation resulting in a more opened position of the fuel valves. However, due to limitations in the CO_2 vaporizer the gas supply pressure had to be reduced during the CO_2 tests to reach high contents of CO_2.

The principle of the test setup was similar to what was used in previous tests [4] for the SGT-700 and SGT-800 gas turbines. Inert gas was fed to the existing natural gas supply system for the engine. The injection of inert gas was done upstream of normal filtration equipment and a 3 m^3 buffer tank. The supply of nitrogen and carbon dioxide was accomplished by vaporizing liquid inert from truck tanks. The vaporization was accomplished with the use of a steam boiler and a heat exchanger. The test equipment was sized to deliver up to around 40vol% of CO_2 and 50vol% of N_2 to the engine.

The injection of inert gas was controlled with a manual valve and the desired flow was communicated from engine operators to operators of the gas supply. This resulted in relatively rough changes in fuel composition and pressure, but this could be handled well by the engine and its control system.

Operation on mixtures of natural gas and CO_2 or N_2 was performed at load points from idle to 100% of full load. The NOx values for stable load points are shown in Figure 6.1. As can be seen, there is no clear difference between N_2- or CO_2-rich gas and no major difference compared to natural gas. The NOx levels measured show capability to run at around 10 ppm from 20-100% load.

In Figure 6.2, the same stable operating points are shown but now as low frequency dynamics vs load. This refers to frequencies lower than 300 Hz higher frequencies are significantly lower and is no risk to operation or safety. All frequencies are well below the alarm level. There is no obvious change in engine behaviour depending on N_2 or CO_2 content compared to natural gas, the gas turbine is operating very stable.

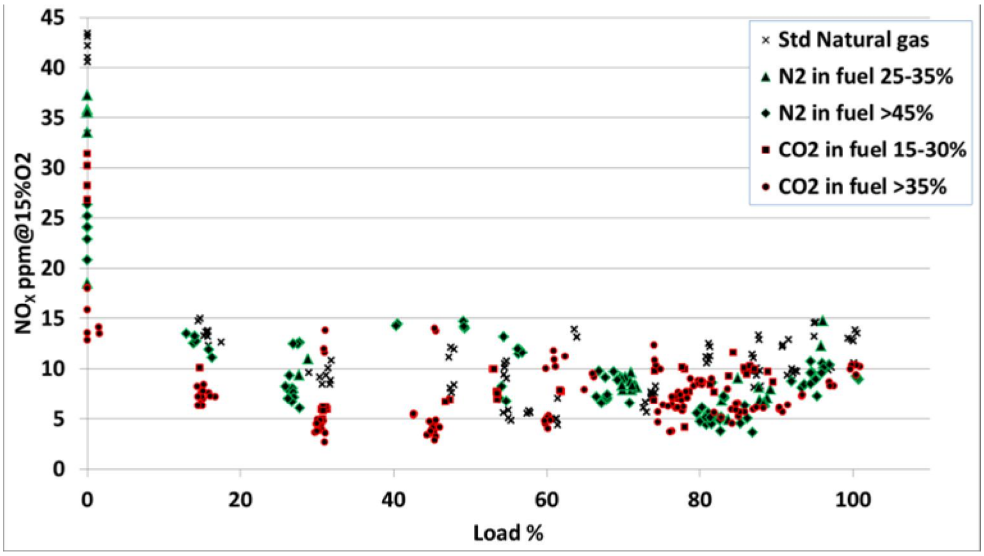

Figure 6.1 NO_x vs Load during stable operation at varying N_2 and CO_2 content.

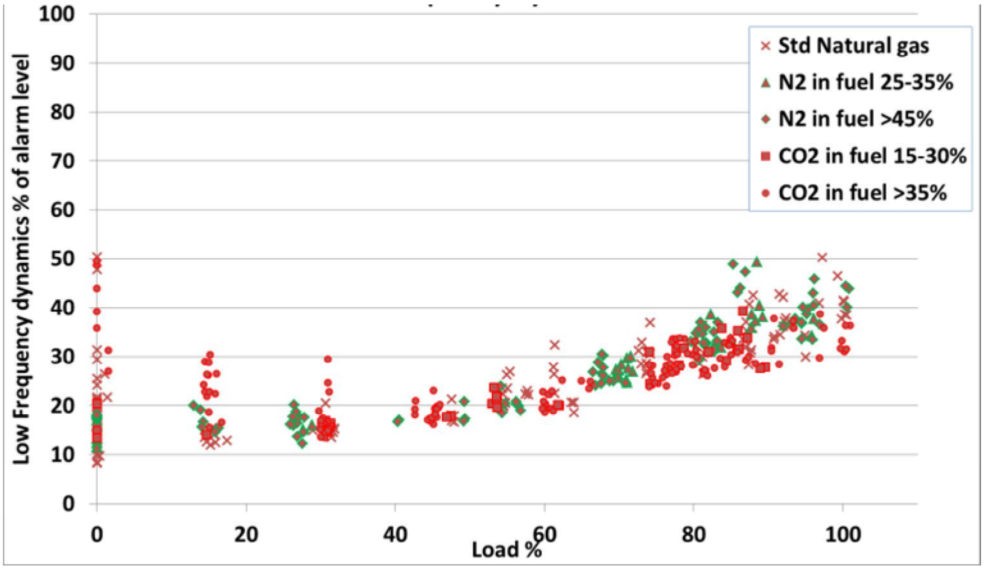

Figure 6.2 Low Frequency Dynamics vs Load during stable operation at varying N_2 and CO_2 content.

From an operator point of view it is likely that the fuel depends on the process and is not of a constant composition and therefore it is obvious there must be a tolerance for changes in gas composition and a good capability to change load rapidly with high inert content in the fuel. For this reason, quite comprehensive testing of transients in fuel composition and load were performed and often in combination. One must bear in mind that fuel mixing was performed manually, which is quite obvious when looking at Figure 6.3, where a test with N_2 is shown.

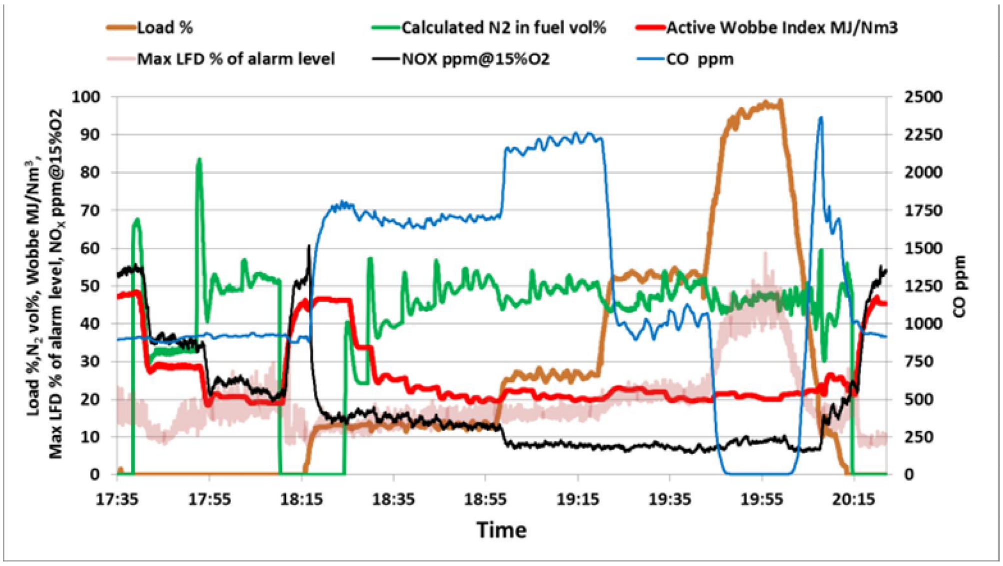

Figure 6.3 Test with nitrogen in fuel at varying load and fuel composition.

The graph in Figure 6.3 shows load and operation results as a function of time, when load is varying from idle to full load and the nitrogen content is varying from 0 to above 50%. Adjustments of nitrogen flow are seen as spikes in the instantly calculated N_2-content of the fuel. However, this value is not totally true as there is a mixing drum, so the resulting actual Active Wobbe Index is a much smoother function. The Wobbe Index shown in the graph is certainly a truer representation of what the engine is experiencing. Wobbe varies between 20 MJ/Nm^3 and 48 MJ/Nm^3, but is around 20 MJ/Nm^3 during the complete load cycle.

Figure 6.3 shows the very low NO_x emissions above 10% load together with the low combustion dynamics over the whole load range. CO-emissions go low above 50% load. The same type of test with CO_2 is shown in Figure 6.4, but due to some limitations of the vaporization system, load was limited to 80% on this occasion as liquid CO_2 entered the fuel.

However, it is not the high load cases that are of main concern for lean gases, so the test is still of interest. It can be seen that NO_x, CO and dynamics are very low above 50% load and a Wobbe Index of around 20 MJ/Nm^3 causes no concerns.

In Figures 6.3 and 6.4, the inert gas is injected at idle load so operation with high inert content could be tested over the whole load range. In Figure 6.5, changes in N_2 content is tested at 70% load with more or less instant changes in N_2 feed to the fuel system. The engine handles the changes well with NO_x emissions continuously below 10 ppm and combustion dynamics well within allowable limits.

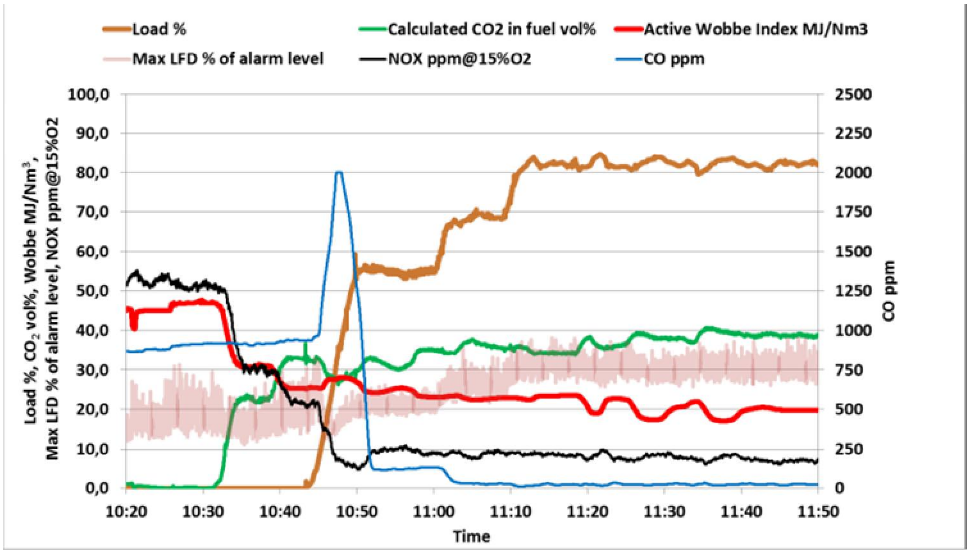

Figure 6.4 Test with carbon dioxide in fuel at varying load and fuel composition.

From a test like this a Wobbe Index change rate can be calculated, as indicated in the figure, giving change rates at 5-10%/s depending on the basis used. This is far above acceptable limits for a fuel flexible combustion system. The same type of tests were performed with CO_2 with similar results.

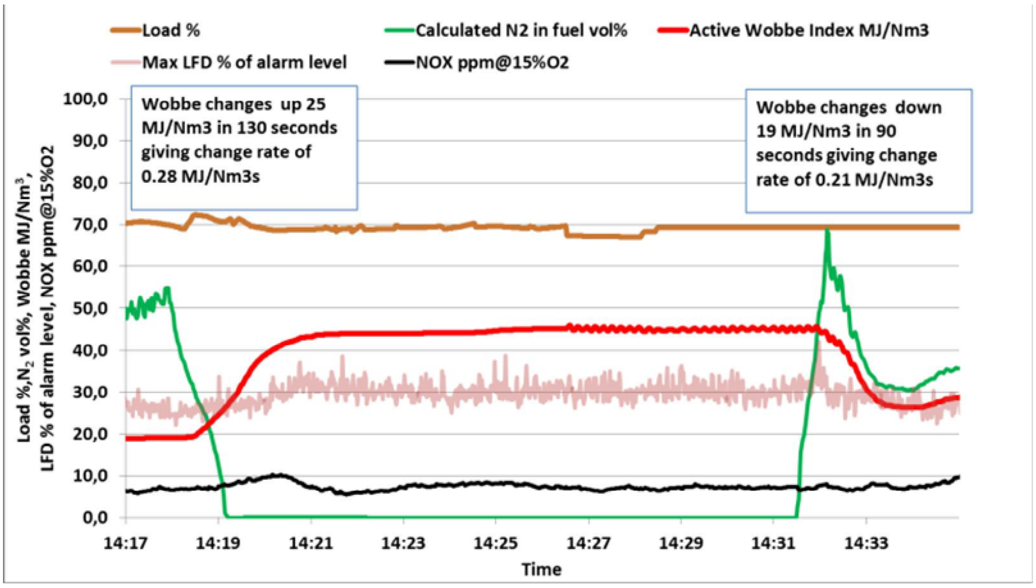

Figure 6.5 Test with nitrogen transient at constant load.

6.2 Ignition and startup tests with high content of CO_2 and N_2

To be able to start on a lean fuel is an important factor for gas turbine operator otherwise it is necessary with a starting fuel and if this can be excluded it is a less complicated installation. Ignition and start up tests were performed with different CO_2 or N_2 fractions in natural gas or methane. It was not possible to mix inert gas and natural gas to a reliable and stable fuel composition, during the transient start up process, with the existing equipment. Consequently, a new way of testing had to be invented and implemented. The procedure for these tests became to fill the 3 m^3 pressure vessel with the gas mixture intended for the test and then ignite and accelerate the engine until gas generator speed controller took over. The start-up gas was injected in the system and left some time for temperature to settle after filling up the pressure vessel. This procedure was first successfully verified on pure natural gas before tests on different gas blends. The tests with CO_2 were done using premixed gas from bottles, which were used to fill the pressure vessel. Mixtures with 15vol% and 20vol% of CO_2 in methane were used. For the tests with N_2, the mixing was done by filling the tank with controlled levels of natural gas and N_2.

The results showed that ignition and acceleration using up to 20vol% CO_2 was possible as well as up to 34vol% N_2. Higher contents were not tested as this was not targeted by the project and the available volume in the test equipment was not enough to support acceleration up to a successful start on leaner gases. The criterion for a successful start was that the gas generator speed controller got into closed loop and normal operation mode. During testing it was apparent that the Wobbe Index used in the control system had to be reasonably accurate, within ±10%, for reliable start-up. An example of a start test is shown in figure 6.6, where a fuel mixture with about 20vol% inert gases was tested.

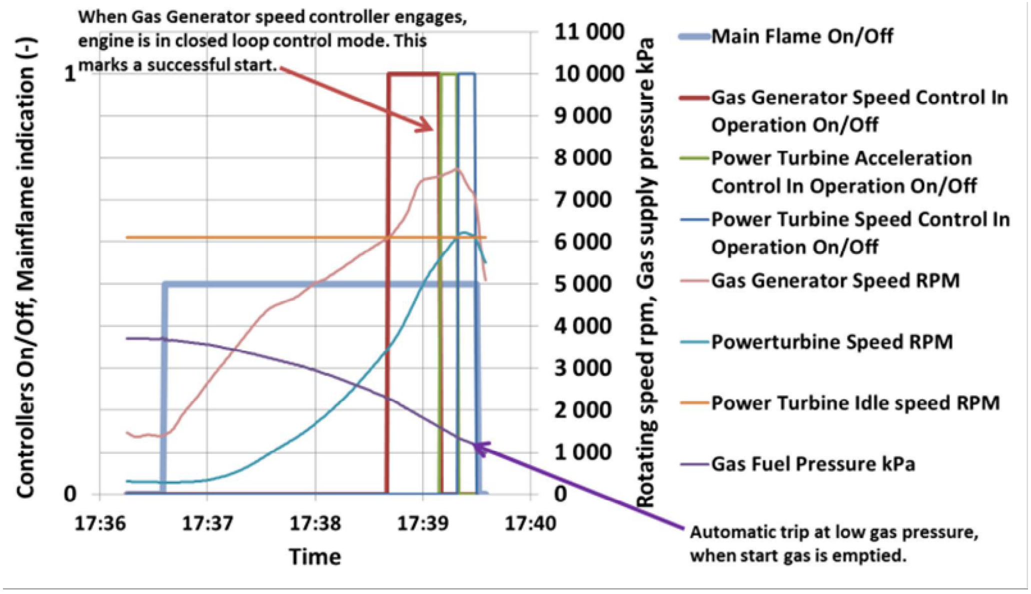

Figure 6.6 Engine start test with 20vol% inert gas in fuel.

The graph in Figure 6.6 shows how power turbine idle speed is reached just before the engine trips due to too low gas pressure. But, as pointed out above, the criterion for a successful start is passed almost one minute before.

7 CONCLUSIONS

The SGT-750 has proven to have a very high tolerance to various types of gaseous fuels during the different tests. All tests have been done with a standard SGT-750 DLE gas turbine with a standard control, combustion and fuel system.

Engine operation, including ignition and starts, of the SGT-750 with high and varying amounts of nitrogen and carbon dioxide in the fuel was successfully proven. The engine operated on fuel containing 50vol% of N_2 or 40vol% of CO_2. Furthermore, start capability was proven on up to 34vol% of N_2 or 20vol% of CO_2. Also, fast fluctuations in fuel composition and pressure were validated with satisfactory results. Emissions on the tested fuel blends were at levels comparable to natural gas operation. The control algorithm which takes care of fuel composition changes, i.e. changes in Wobbe Index was proven to be fast and reliable and has allowed rapid changes in fuel composition. After the tests the gas turbine was inspected and no wear or damages were detected.

The complete combustion operation envelope at arctic conditions for the SGT-750 burner was verified in a high pressure test rig. The fuel compositions explored during engine testing proved to be achievable also at equivalent ambient temperatures down to -60°C.

The ignition capability and reliability at arctic conditions were tested at atmospheric conditions with a single burner setup. It was verified that ignition is reliable using up to 55vol% of N_2 and 30vol% of CO_2 at air temperatures down to -60°C.

The single burner high pressure test campaign was also used to validate the fuel flexibility capabilities for highly reactive fuels. The standard SGT-750 burner showed to be capable of operating on high fractions of ethane, propane, butane and hydrogen while maintaining low NO_x emissions. The maximum levels tested for ethane, propane and butane concentrations were limited by the test facility. For cases with hydrogen mixtures it was possible to test without flow limitations and it was shown that low NO_x emissions were achievable for H_2 concentrations up to 47vol%.

As stability and emissions were recorded at acceptable levels both for inert and reactive gas it implies that the fuel/air mixing is acceptable with unchanged gas fuel nozzle sizes. The results achieved for both inerts and highly reactive fuels represent a validation of the standard SGT-750 gas fuel acceptance limits. The test results represent a valuable start reference for further development of the fuel flexibility for the combustion system.

NOMENCLATURE

C2H6	Ethane
C3H8	Propane
C4H10	Butane
CO	Carbon monoxide
CO2	Carbon dioxide
DLE	Dry Low Emissions
DLR	Deutsches Zentrum für Luft- und Raumfahrt
H2	Hydrogen
HPCR	High Pressure Combustion Rig
ISO	International Organization for Standardization
LFD	Low Frequency Dynamics
N2	Nitrogen
NG	Natural Gas
NOx	Nitrogen oxides
RPL	Rich Pilot Lean combustor
WI	Wobbe Index

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