PENTANE RICH FUELS FOR STANDARD SIEMENS DLE GAS TURBINES

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ABSTRACT

Associated gases at oil wells are often rich in heavy hydrocarbons (HHC, here denoting hydrocarbons heavier than propane). HHC cause handling difficulties and the combustion properties are quite different from standard natural gas. For this and other reasons HHC rich associated gases are often flared or vented. This is an enormous waste of useable energy and a significant contribution to emissions of pollutants, global CO_2 and other greenhouse gases.

Siemens Industrial Turbomachinery AB in Finspong (SIT AB) recently tested a standard DLE 25 MW SGT-600 gas turbine and a standard 31 MW SGT-700 gas turbine with HHC rich natural gas. Pentane was chosen as a model substance for HHC. The tested gases had up to 30% of the fuel heating value from pentane.

The unmodified standard DLE gas turbines proved to be very tolerant to the tested pentane rich gases. CO emissions were reduced with increasing pentane content in the fuel for the same power output. NOx was observed to increase linearly with the pentane content. Combustion dynamics was affected mildly, but noticeably by the pentane rich fuel.

This result, together with earlier presented results for the same DLE engines on nitrogen rich natural gases, gives an accepted and tested total LHV range of 25-50 MJ/kg and Wobbe index range of 25-55 MJ/Nm³. No special adaptation of the gas turbines was necessary for allowing this wide fuel range.

The benefit of increased and proven fuel flexibility is obvious as it allows the gas turbine owner to make full use of opportunity fuels and to supply power at low fuel cost.

NOMENCLATURE

AIT	Auto ignition temperature
DLE	Dry low emissions
GT	Gas turbine
HFD	High frequency dynamics 200-1000Hz (for SGT-
	600)

HHC	Heavy hydrocarbons (heavier than propane)
LFD	Low frequency dynamics <200 Hz
LHV	Lower heating value
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
MFD	Medium frequency dynamics 200-600 Hz (for
	SGT-700)
NG	Natural gas
PFR	Pilot fuel ratio
τ_{mix}	Physical delay time
$\tau_{\rm chem}$	Chemical delay time
TRIFS	Test rig flexible system.
T _{flame}	Flame temperature

INTRODUCTION

From a gas turbine manufacturer perspective, it has been noted that there is a continuously increasing customer interest in gas turbine combustion of gases containing increasing amounts of heavy hydrocarbons, HHC.

HHC rich gases: sources and uses

The main sources of HHC rich gases are associated gas from oil wells or hydrocarbons from processing of liquefied natural gas, LNG.

Associated gas from oil wells is often far from as pure as a typical pipeline natural gas which almost entirely consists of methane. Among unwanted components such as water, nitrogen, carbon dioxide and sulfur, associated gas often contains significant fractions of HHC (such as butanes and pentanes) resulting in difficulties with pipeline transporting. Also, there is often a great distance separating potential markets from oil production areas making it difficult and costly with processing and transportation. As a result of these and other problems it is common that an important part, and sometimes the whole stream of the associated gas is being flared, wasting a valuable feedstock for energy production and contaminating the environment.

In the last fifteen years, global gas flaring has been estimated to be in the range of 140 to 170 billion cubic meters annually [1]. The 2008 gas flaring estimate represents 21% of the natural gas consumption of the USA and added more than 278 million metric tons of carbon dioxide equivalents into the atmosphere. In addition, a large amount of gas is also estimated to be vented in the oil and gas sector each year. An attractive part of the solution to the problem with gas flaring and venting is to burn the associated gas in gas turbines for power generation. The NOx emissions from a modern gas turbine are substantially lower than the NOx released from a utility flare stack. The total amount of fuel flared is enough to run in the order of 2400 25MW engines which in total could deliver 60 000 MW of electrical power.

Another source of potential gas turbine fuel that may contain high fractions of HHC, mainly pentane, is gases from processing of liquefied natural gas, LNG. To fulfill LNG requirements, most of the HHC have to be removed from the raw gas to avoid ice formation in the LNG process. Also, to fulfill vapor pressure requirements it may be necessary to extract the most volatile fraction, i.e. pentane, from the condensate product and route this stream to a dedicated pentane fuel system. For the LNG plant it could be an attractive option to add the pentane to a gas turbine fuel stream.

HHC rich gases as fuel in gas turbines

There are several potential problems using gases containing high amounts of HHC in gas turbines, especially in premixed low NOx combustor systems. Apart from obvious widened operating range of the fuel gas conditioning equipment, main concerns with heavy hydrocarbons are the effect of generally quicker and more intense combustion which may have an effect on:

- Flame stability and combustion dynamics
- Flame position and the risk for autoignition/flashback and ultimately the mechanical integrity of the combustor/gas turbine system
- Temperature distribution in the combustion system
- Emissions of NOx and CO
- Behavior of the engine control system

For premixed low NOx systems, the risk for autoignition in the mixing zone of fuel and air is of particular concern. It is well known that autoignition temperatures, AIT, are decreased by the addition of heavy hydrocarbons to a methane based fuel as well as the autoignition delay time [2]. Residence times for premixed compositions must be shorter than the mixture's autoignition time at a given temperature and pressure to avoid pre-flame ignition [3].

Autoignition - Either a temperature or a delay time can quantify autoignition. The autoignition temperature, (*Figure 1*) is the minimum temperature at which a combustible mixture ignites with no external ignition source. The AIT for

hydrocarbon/air mixtures decreases with increasing chain length and is higher for branched hydrocarbons than for straight hydrocarbons. Higher pressure will decrease AIT. In general, the temperature of the gas turbine compressor air is above the AIT for fuels containing heavy hydrocarbons and the parameter of interest is then the autoignition delay time. The autoignition delay time has two components: The physical delay time, τ_{mix} , including heat transfer and mixing of fuel and air and the chemical delay time, τ_{chem} . Upon changes in gas composition and pressure, τ_{chem} will show a similar trend as AIT, i.e. increase in pressure will shorten τ_{chem} as will an increase in HHC content.



Figure 1. Minimum autoignition temperature vs carbon chain length (*atmospheric pressure*). [4]

For the combustion systems tested here, corresponding to lean premixed conditions, the goal is to have a nearly homogenous mixture prior to combustion. As a result, in these systems, the mixing time is relatively short compared to chemical delay and thus the ignition delay time depends largely on the chemical kinetics. In *Figure 1* the preheat temperature ranges of typical aeroderivative GTs and typical industrial GTs, that run at lower pressure, are indicated.

Burning velocity - HHC have slightly higher laminar burning velocity than methane, which normally is the main constituent of NG. The maximum flame speed in air at atmospheric pressure is approximately 42.5 cm/s for n-pentane and 37.3 cm/s for methane [5]. However, no component typical of HHC is near the maximum flame speed of hydrogen, given as 291.2 cm/s in the same reference. It must be kept in mind that minimum AIT for hydrogen is rather high, given as 571°C in [5], so even though ignition delay time might be low for hydrogen at high temperatures it does not normally cause flashback through short ignition delay time at typical gas turbine preheat temperatures. Consequently, hydrogen initiated flashback is normally caused by its high burning velocity. Pure HHC flame speed initiated flashback is not likely to occur in a well designed DLE burner as testing with hydrogen is normally done during the design phase. The DLE burners considered here have been tested thoroughly with hydrogen, up to 90% hydrogen in NG or nitrogen at atmospheric conditions, so flashback due to HHC flame speed is not considered further in this work.

Dew point - The dew point of a gas mixture is the temperature at which the first droplets of hydrocarbons or water form when the gas is being cooled and/or compressed. *Figure 2* shows the dew point versus pentane content in natural gas for a gas pressure of 27 bar(a). The dew point for a natural gas with 10% by volume of pentane is around 55° C at 27 bar(a) depending on the exact composition and distribution of isomers in the gas.



Figure 2. Dew point vs pentane concentration in NG at 27 bar(a).

To investigate the above mentioned HHC issues, Siemens Industrial Turbomachinery AB in Finspong, Sweden, decided to test a standard DLE 25 MW SGT-600 gas turbine and a standard 31 MW SGT-700 gas turbine with simulated HHC rich natural gas using pentane, C_5H_{12} , as a model substance for HHC. Full scale engine tests were performed in the TRIFS test facility in Finspong. The test rig is described in [6].

Pentane was used as model substance for HHC since it was identified to have/to be:

- Low autoignition temperature, comparable with even heavier hydrocarbons (*Figure 1*)
- Short ignition delay time, comparable with even heavier hydrocarbons
- "By-product" in LNG processing
- Reasonable thermodynamic properties, making it possible to test relatively high fractions in existing standard SGT-600/700 gas supply system set up
- Available to be bought and handled at reasonable effort in Sweden.

SGT-600, SGT-700 and SGT-800 DLE combustion systems - The 2^{nd} generation DLE burner was developed to meet the increased emissions requirements for the on-shore market. It was introduced in the SGT-600 25 MW gas turbine in 1991, see *Figure 3*. The SGT-600 system is capable of emission levels as low as 25 ppm NOx using natural gas fuel. For conventional (non-DLE) combustion on liquid fuel, water injection is still used to lower the flame temperature and achieve emission levels as low as 42 ppm NOx [7, 8]. The DLE burner is a split cone with two main fuel pipes. The combustion air enters in the two slots at rather high velocity, where also main fuel (stage 2) is injected from the main fuel pipes perpendicular to the air flow in order to achieve mixing. The injection of pilot gaseous fuel (stage 1) as well as main liquid fuel is positioned in the centre of the burner.



Figure 3. The 2nd generation DLE burner used in SGT-600.

During the development of SGT-700 (31 MW) and SGT-800 (47 MW) in the 1990's, the DLE technology was brought one step further. By using the experience from the 2^{nd} generation technology the idea was to decrease NOx emissions further with natural gas fuel and create a burner that can deliver dry low emissions also with liquid fuel. The 3^{rd} generation DLE system was successfully tested and verified during the SGT-800 first fire in 1998. The same burner is used in the SGT-700 and delivers 15 ppm NOx emissions on natural gas and 42 ppm NOx on liquid fuel [6]. This burner, *Figure 4*, consists of a split cone forming four air slots where 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 compressor air. The pilot fuel injection is positioned at the burner tip.



Figure 4. The 3rd generation DLE burner for SGT-700 and SGT-800.

Typical flame appearance in the SGT-800 combustor at engine condition is shown in *Figure 5*. The flame is positioned in the burner outlet. Small pilot flames are also visible.



Figure 5. Flame appearance during operation in SGT-800.

To achieve optimum emissions and low levels of combustion dynamics it is of key importance to control piloting and flame temperature and consequently combustion stability. Flame temperature can be influenced via controlling the airflow to the burners. Increased flame temperature can be achieved by turning suitable variable compressor guide vanes or by using a combustor bypass or through bleeding compressor air. The latter is of course negative for GT efficiency.

A combustor bypass can increase the flame temperature by reducing the air flow trough the burners without affecting the GT efficiency. The SGT-600 combustor bypass system, as illustrated in *Figure 6*, is integrated with the turbine casing and consists of 6 valves controlled by one actuator.



Figure 6. SGT-600 bypass system used to increase the flame temperature between 0 and 90% load.

The described combustion systems have accumulated several million hours of operation on a variety of fuels in different environments. However, the fuel limitations are by no means fully explored and there is a continuous expansion of the accepted fuel range. Tests have been performed at different situations ranging from single burner tests in rigs to full size engine tests. A short summary of the engine combustion systems, previous engine experiences and some fuel types tested are given in the table below.

	SGT-600	SGT-700	SGT-800
Engine size and type	25MW Twin- shaft	31MW Twin- shaft	47MW Single- shaft
DLE combustion system	2 nd generation with bypass and bleed	3 rd generation with bypass	3 rd generation with compr. guide vanes
Typical emissions at full load on NG	NOx 23ppm CO 25ppm	NOx 15ppm CO 5ppm	NOx 12ppm CO 2ppm
Engine test possibility	TRIFS	TRIFS	Customer site only
Performed fuel flex testing on NG-type fuels with standard engine	25vol% N ₂ - diluted NG [9] 100% LPG This test	40vol% N ₂ - diluted NG [10] This test	50vol% N ₂ - diluted NG [11]

Table 1. Available SIT DLE gas turbines 25-50 MW range

HHC rich gases test: SIT Project scope

Investigating the potential of SGT-600, SGT-700 and SGT-800 with DLE combustion systems to operate on gas containing HHC should be performed through injecting pentane in the normal fuel gas stream and simultaneously monitor:

- GT Control system behavior
- Flue gas emissions
- Combustor dynamics
- Burner pressure drop
- Combustion system temperature distribution
- Fuel gas temperature and possible liquid droplet formation

The gas turbines should be inspected in the combustion zones and burners after the tests.

As only SGT-600 and SGT-700 can be operated in the TRIFS test facility the project only comprises full scale engine tests on these two engines. Analysis of the result and the fact that the same burner is used in SGT-700 and SGT-800 should be enough to also make conclusions on SGT-800.

The goal is to add up to 10% by volume of pentane (C_5H_{12}) , corresponding to approximately 30% of total heating value, into the NG. The reason for choosing 10% by volume of pentane as a maximum for testing is that it is a good trade off between current market demand and complexity for testing. The higher pentane content there is in the gas, the larger installations in terms of heat tracing, pre heating and insulation is needed. The TRIFS test rig was built for a gas temperature of 60 °C and major modifications would have been necessary for higher fractions.

The main focus of testing is to evaluate the risk for flashback and autoignition.

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EXPERIMENTAL SETUP

A plant for feeding and mixing pentane into natural gas had to be designed and built. The concept chosen was to spray liquid pentane into the natural gas fuel flow in a well mixed and homogeneously heated way, thereby supplying an engine with a gas containing 90-100% by volume of natural gas, and 0-10% by volume of pentane,

The pentane mixing unit was designed for a capacity of one liter pentane per second and a storage capability of $10m^3$ pentane at 0°C. The pentane was pumped by a dosage pump through a steam heat exchanger where the temperature of the pentane was increased to approximately 150°C at 40 bar. The liquid pentane was then sprayed with nozzles into the natural gas flow for vaporization. An overview of the facility is shown in *Figure 7*. Close ups on mixing unit are shown in *Figure 8* and *Figure 9*.



Figure 7. Pentane mixing unit.

To enhance mixing between pentane and NG and reduce the effects from sudden transitions, a buffer tank with a design pressure of 40 bar and a volume of $3m^3$ was installed.



Figure 8. Steam boiler, pump and nozzles were operated manually.

Most NG piping and pentane piping were equipped with heat tracing cables and insulation to avoid condensation.

An application for temporary handling of flammable goods was handed in to the local fire brigade and an environmental related application was granted by the regional authorities. The municipal fire brigade was present at the tests with one truck and two firemen.



Figure 9. Pump operator, pump and buffer tank.

HHC RICH GASES TESTS

The tests were performed during a total of 4 days of operation in Spring 2010, two days with a SGT-600 and two days with a SGT-700. Operation went well and was very smooth. No significant upsets occurred, even though there were some initial problems with the pentane mixing unit. Both engines ran on approximately 10% by volume of pentane. Slightly higher fractions were recorded on part load. The limits of the gas heating equipment were fully explored.

About $20m^3$ of liquid pentane (13 tons) was consumed during the tests. It was burnt at various loads and at different operating conditions.

Pentane and NG compositions are given in Table 2.

Table 2. Fuel compositions to be mixed

<i>Tuble 2. Fuel compositions to be mixed</i>						
Pentane	weight%	Natural gas	vol%			
Methane	0.0	Methane	98.0			
Ethane	0.0	Ethane	0.7			
Propane	0.0	Propane	0.3			
Butane	0.0	Butane	0.0			
N-pentane	84.0	N-pentane	0.0			
I-pentane	15.5	I-pentane	0.0			
Hexane+	0.5	Hexane	0.0			
Nitrogen	0.0	Nitrogen	1.0			

Engine operation

Engine operation showed minimal sensitivity to the fuel mixtures tested. Load was very stable and only the gas control valves reacted to the change in fuel composition. Combustion system was virtually unaffected by the change in fuels, e.g. temperature outlet distribution and burner temperatures. Valuable operational experiences were gained and new gas distribution/pilot schedules were investigated and partly implemented.

Engine control was tested and found to handle Wobbe index transients very well as can be seen in *Figure 10* below, where pentane feed is stopped in SGT-700 and Wobbe index drops.

A comparison can be made with earlier tests on the same engine type with nitrogen diluted NG [7]. Shutting down nitrogen feed will push Wobbe index up and also this works well as can be seen in *Figure 11*.



Figure 10. Stopping pentane supply (10 vol%) at full load 30 MW in SGT-700. Wobbe index decrease from 54 to 47 MJ/Nm³.



Figure 11. Stopping nitrogen supply (40 vol%) at 20 MW in SGT-700. Wobbe index increase from 25 to 47 MJ/Nm³. See also [6].

More details on the results from each engine are given below.

Results SGT-600

NOx and CO emissions - *Figure 12* depicts NOx and CO emissions as function of fuel pentane content when operating at full load with 21% PFR (pilot fuel ratio). NOx increases linearly with the increment of pentane. It increases at approximately 0.6 ppm NOx per % by volume of pentane. During the tests, focus was not on optimizing emissions. Pilot fuel was set at a rather conservative level.

CO behaves differently as it diminishes dramatically. The CO emissions reduce steadily from around 35 ppm to below 10 ppm after reaching 7% by volume of pentane. Thereafter, the reduction is less pronounced and stabilizes at about 5 ppm.



Figure 12. SGT-600 at full load and 21% PFR. NOx(\blacklozenge) and CO() vs pentane content in fuel.

Combustion dynamics - *Figure 13* shows Low Frequency Dynamics (LFD) and High Frequency Dynamics (HFD) as function of pentane content in fuel. The data is shown as % of trip level. For HFD there is a slight increase when the pentane percentage increases. When analyzing the frequency signal there is not a particular frequency increase, but a general increase in the whole analyzed frequency range. A similar increase in HFD is observed when PFR is decreased at full load (see below).

PFR variation - *Figure 14* shows the influence of PFR on NOx and CO at full load on NG. The same is shown in *Figure 15* but with 8-9% by volume of pentane in the fuel. As the figures show, the effect of PFR variation is close to linear for NOx emissions and NOx increase almost parallel for the two cases. The offset value is approximately 7 ppm higher NOx for pentane addition.



Figure 13. SGT-600 at full load and 21% PFR. LFD (\blacklozenge) and HFD () vs pentane content in fuel.

CO emissions are affected drastically when pentane is added. The emissions drop from approximately 25 ppm (*Figure 14*) to below 5 ppm when pentane is added (*Figure 15*). Apparently it is not very much affected by the PFR variation.

The effect of PFR variation on LFD and HFD are depicted in *Figure 16* for NG and *Figure 17* for pentane rich NG. LFD increases slightly if the PFR is reduced and it indicates a negative effect in the flame stability when using low PFR values. However, in the tests performed, really low piloting was never tested with SGT-600. In case of adding pentane to the fuel this negative effect is reduced. Adding pentane to the fuel reduces LFD (increases flame stability). Pentane addition produces slightly higher HFD at PFR greater than 16% PFR and lower HFD below 16% PFR compared to natural gas only.



Figure 14. SGT-600 at full load and 0 vol% pentane in fuel. NOx (\blacklozenge) and CO () vs PFR.

It is interesting to note that the NOx increase experienced in SGT-600 with pentane addition can be counteracted with a PFR reduction, without a significant penalty in combustion dynamics. With pentane, PFR need to be at 13% to reach 25 ppm NOx. Without pentane, the 25 ppm level is reached at 17% PFR.



Figure 15. SGT-600 at full load and 8-9 vol% pentane in fuel. NOx (\bullet) and CO () vs PFR.



Figure 16. SGT-600 at full load and 0 vol% pentane in fuel. LFD (\blacklozenge) and HFD () vs PFR.



Figure 17. SGT-600 at full load and 8-9 vol% pentane in fuel. LFD (♦) and HFD () vs PFR.

Inspection of hardware - A thorough boroscopic inspection showed no visible effects of the pentane test.

Results SGT-700

NOx and CO emissions - *Figure 18* shows the effect of pentane increase in the fuel on NOx/CO emissions at full load.

As it was observed in the case of SGT-600 there is a linear increase in NOx emissions once the pentane percentage of the fuel increases. The rate is approximately 0.5 ppm NOx per percentage point increment of pentane in the fuel. CO emissions show scattered values at around 2 ppm. During the tests, focus was not on optimizing emissions, thus there was no time spent on tuning.



Figure 18. SGT-700 at full load and 2% PFR. NOx(\blacklozenge) and CO() vs pentane content in fuel.

Combustion dynamics - LFD is very stable, independent of pentane content. MFD show a small increase when reaching 9% by volume of pentane in the mixture. As in the case of the SGT-600 there is not a particular frequency increase but a general noise increase through the whole frequency range.



Figure 19. SGT-700 at full load and 2% PFR. LFD (♦) *and MFD* () *vs pentane content in fuel.*

Part load - *Figure 20* depicts emissions at 15 MW. NOx increases from 30 ppm to 35 ppm with the content of pentane. However the most important effect occurs with the CO emission that drops from above 200 ppm down to below 25 ppm. It is only at lower loads that CO is emitted from SGT-700. LFD and MFD remain constant.



Figure 20. SGT-700 at 50% load and 17% PFR and open bypass. $NOx(\blacklozenge)$ and CO() vs pentane content in fuel.

Inspection of hardware - A thorough boroscopic inspection showed no visible effects of the pentane test.

DISCUSSION - ANALYSIS

One of the most interesting phenomena found in the tests is the increase in NOx emissions and reduction in CO emissions as function of pentane content in the fuel. One possible explanation could be that the adiabatic flame temperature of pentane obviously is higher and it could all be a temperature effect.

A GT performance calculation shows the adiabatic flame temperature increase with pentane content, see *Figure 21*.



Figure 21. SGT-600(-----) and SGT-700 (-----) Full load flame temperature increase calculation vs pentane content.

This small increase in flame temperature can possibly explain around 2 ppm out of the 5 ppm NOx increase seen in both engines.

To explain the phenomena also the flame distribution will have had to change. The faster chemistry probably makes the flames slightly less well mixed prior to ignition and probably moves the flames closer into the burner. This is indicated in *Figure 22* were the pressure drop over the combustion system increases as pentane content rises in SGT-700, part load. This coincides with improved CO burnout. An increased pressure drop indicates a flame closer to the burner, obstructing the

burner outlet (see *Figure 5*). Possible changes in the burning velocity also act in the same direction of change. Tendencies of flashback was seen in SGT-700 for maximum pentane content at full load, but was easily counteracted with proper tuning of gas distribution in the burners.



Figure 22. SGT-700 at 50% load and 17% PFR and open bypass. $dP(\blacklozenge)$ and CO() *vs pentane content in fuel.*

The test results were produced at specific ambient conditions and at specific engine conditions. To be really useful results, there must be a way to transfer the results to other ambient conditions, fuel compositions and engine conditions. The authors approach is to look at ignition delay times theoretically and regard the test results at actual conditions as datum tests, meaning verified possible operating points for the combustion system in question. This means that every successful test can be considered to show that the theoretically calculated ignition delay time is acceptable, as no flashback occurred at the actual conditions. With this approach, using normalized ignition delay time from datum test, we can theoretically investigate the effects of ambient, fuel and engine conditions. However, we must keep in mind that the calculated ignition delay time is not a limit of the combustion system; it is only a verified, acceptable operating point from an ignition delay time perspective with flashback issues primarily in focus. This will be elaborated on further below.

Other aspects, as mentioned in the introduction, must be evaluated separately, e.g. dew point, emissions and dynamics as they are obviously not so strongly related to ignition delay time. However, pentane is likely to be a greater challenge for a combustion system than e.g. propane.

Ignition delay time calculations

As mentioned above, autoignition within the premixing zone of low NOx burners constitute a potential problem and a worst case scenario for fuels with an elevated amount of HHC. In this section, results from chemical kinetic modeling are presented. Calculated autoignition delay times for the performed test conditions are used as a reference for comparison with autoignition delay times for other conditions and other fuel blends containing heavy hydrocarbons such as butanes and pentanes.

Calculations were performed in Chemkin 4.1 using a closed homogeneous constant pressure reactor to study τ_{chem} , i.e. the reactant mixture is assumed to be homogeneous (infinitely fast mixing in the mixing zone). The closed homogeneous reactor requires, apart from infinitely fast mixing, many other assumptions and simplifications for ignition delay applications:

- Mass transport is assumed infinitely fast
- No inflow or outflow
- Only gas-phase reactions
- Ideal gas behavior

The closed homogeneous reactor is a spherical reactor containing a perfectly mixed gas, allowed to react starting from an initial time. The inner shell is allowed to expand and increasing the volume, enable reactions to occur at constant pressure.

For the closed homogeneous reactor, the ignition delay time was determined by finding the maximum temperature gradient and by determining local maximum of radical species concentration.

As input to the modeling it is necessary to specify conditions such as composition of fuel and air, equivalence ratio (ϕ) , pressure, and initial temperature. Generally, increasing equivalence ratio, pressure and temperature decreases the autoignition delay time. For these calculations it is always assumed that the equivalence ratio is 0.5, which represents close to the global conditions for a gas turbine combustor. For local zones with richer mixtures, a much shorter ignition delay time is expected. Values for temperatures and pressures are either taken from actual values from the engine tests or standard data for the respective engine.

The mechanism of Curran et al. [12] was used to model the formation and consumption of chemical species. Some validation of the calculations was also done by comparing with the experimental data by Bourque et al. [2] and this showed reasonably good agreement.

The effect on the ignition delay time by adding pentane to a standard natural gas is shown in *Figure 23*. It can be seen that at a content of 10% by volume of pentane, the ignition delay time is less than 10% of that for a standard natural gas. The effect of adding pentane is lower at higher temperatures (not illustrated).



Figure 23. Autoignition delay for natural gas with varying amount of pentane. Initial conditions: $T = 550^{\circ}$ C, p = 20 bar(a), $\phi = 0.5$. (Normalization to a standard natural gas)

Calculations were also made for SGT-700 full load conditions at different ambient temperatures to see if the test results could be applied also for conditions other than those tested, see *Figure 24*. The ignition delay time is fairly constant at higher ambient temperatures. The explanation is that a change in ambient temperature results in an increase in combustor inlet temperature at the same time as the combustor inlet pressure decreases. Those effects influence the delay time in opposite directions, thus not giving any net change. At low ambient temperatures, the low combustor inlet temperature is a limiting factor for the autoignition delay time, suggesting that there is a greater margin towards autoignition in the mixing zone.



Figure 24. Autoignition delay time at SGT-700 full load for natural gas/pentane mixture (9% by volume of pentane) with varying ambient temperature. (Normalization to tested conditions).

The ignition delay time is greatly affected by the branching of the heavy hydrocarbon isomers. A branched molecule is less reactive and has a longer autoignition delay time than a straight alkane. The difference in ignition behavior for the different pentane isomers is thoroughly described by Ribaucour et al. [13]. The pentane used in the tests contain a much higher fraction of the more reactive straight pentane isomer, n-pentane, than any sample found for naturally occurring associated gases or natural gases. In LNG production, the fraction of n-pentane that may end up in fuel gases is usually even lower. To obtain an appropriate vapor pressure of the produced condensate it is sometimes necessary to remove isopentane, which is slightly more volatile than n-pentane. The removed isopentane may then end up in a fuel gas stream. This implies that the tested pentane is much worse from an autoignition/pre-ignition point of view than what is normally found in fuel gases. The fraction of n-pentane in total pentane for 100 different samples (from Siemens internal fuel database and [14]) is illustrated in *Figure 25*. A maximum fraction of around 65% n-pentane is found and this amount is used in the following calculations.



Figure 25. *n*-pentane fraction in total pentane for 100 different gases. Δ =tested pentane composition

The naturally occurring distribution of butanes has also been extracted from 100 different gas compositions, see *Figure 26*. A maximum content of around 77% n-butane is found and this amount is used in the following calculations.



Figure 26. n-butane fraction in total butane for 100 different gases.

In terms of autoignition, the SGT-700 engine test (assuming 9% by volume of pentane) corresponds to approximately 11% by volume of the most reactive pentane found in the compilation. This is illustrated in *Figure 27*.

The same principle is used in order to show how much butane (C_4H_{10}) the test with pentane corresponds to. This is also illustrated in *Figure 27*. At these conditions, a natural gas with around 14-15% by volume of butane will have the same ignition delay time as the tested gas composition.

The autoignition delay time for hydrocarbons heavier than pentane does not decrease drastically [12]. Also, hexane and heavier hydrocarbons will rarely be found in more than maximum a few percentages in a fuel that is in gaseous state at the fuel supply conditions for gas turbines. There is not much information available about the distribution of different hexane (C_6H_{14}) isomers in literature or in the internal fuel database, but an attempt to show the relevance of the test for a representative hexane distribution is also shown in *Figure 27*. The kinetic mechanism used does not contain branched hexane isomers and they have been modeled as the straight chained alkane that corresponds to the longest carbon chain in the hexane isomer. According to these calculations, the test with pentane would correspond to around 8-9% by volume of hexane.



Figure 27. Autoignition delay for varying amount of HHC.

···· Butane (77% n-butane, 23% isobutane)

— Pentane (65% n-pentane, 35% isopentane).

 Hexane (30% n-hexane; 40% 2-methylpentane, 3-methylpentane; 30% 2,3-dimethylbutane/2,2-dimethylbutane)

(Normalization to 9% of tested pentane composition and engine conditions).

The largest engine in the Finspong range, SGT-800, was not included in the actual test. However, calculations have been performed in order to see how much pentane that could be allowed in the SGT-800 based on the tests on SGT-600/700. The SGT-800 operates at a slightly higher temperature and pressure, but has a similar DLE combustion system as the SGT-700. In terms of autoignition, the SGT-700 engine test with 9% by volume of pentane corresponds to approximately 9-10% by volume of the most reactive pentane for the SGT-800. This is illustrated in *Figure 28*



Figure 28. Autoignition delay for natural gas with varying amount of pentane (65% n-pentane, 35% isopentane) for SGT-800 mixing zone conditions. (Normalization to 9% of tested pentane composition and engine conditions).

CONCLUSIONS

Tests and calculations show that it is possible to operate the Siemens unmodified DLE engines SGT-600, SGT-700 and SGT-800 with a NG fuel containing up to at least 10% by volume of pentane, meaning approximately 33% by weight or 30% by heating value.

This result, together with earlier presented results, [9, 10, 11] for the same DLE engines on nitrogen rich natural gases, typical of LNG boil off gas, give an accepted and tested total range of LHV values of 25-50 MJ/kg and a range of Wobbe index of 25-55 MJ/Nm3. No special adaptation of the gas turbines was necessary for allowing this wide fuel range.

The tests show that engine and engine control systems can handle transients when Wobbe index changes rapidly.

Emissions were affected the same way in both tested engines, i.e. with a small increase in NOx emissions and a significant drop in unburned and CO emissions as HHC content increased. For SGT-600 this NOx increase can be counteracted through lowering the pilot fuel flow. SGT-700 measurement indicated that the main reason for this NOx increase was that the flame moved closer into the burner outlet. This was indicated by the increase in burner pressure drop. With proper burner tuning there was no indication of flashback. Combustion dynamics were almost unaffected by the addition of HHC. Combustion system temperatures did not indicate any significant changes from pentane in fuel.

A theoretical procedure is proposed and investigated regarding how other components in the fuel and varying operating conditions can be accounted for, from an ignition delay time perspective. With the proposed method it is shown that for worst case isomer mixtures it is equivalent with 8% hexanes or 11% pentanes or 14% butanes, at SGT-700 tested conditions. The same procedure is used for making predictions on SGT-800, which indicates smooth operation with worst case pentane isomer mixture content up to at least 9-10%.

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FUTURE WORK

The limiting factor to test higher pentane concentrations was the high dew point in combination with fuel system limitations. The supply temperature has to be well above the dew point in order to avoid that condensates enter the engine. Using a heat exchanger on the natural gas supply side would give better possibilities of testing higher concentrations.

It would also be possible to test other fuel mixtures with almost the same experimental setup, e.g. butane in natural gas. This would give valuable insight into the influences of HHC composition.

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