The Future of Gas Turbine Technology
8th International Gas Turbine Conference
12-13 October 2016, Brussels, Belgium

Paper ID Number (*09-IGTC16)*

GAS FUEL FLEXIBILITY IN DRY LOW EMISSIONS COMBUSTION SYSTEMS

Michael Welch, Brian Igoe
Siemens Industrial Turbomachinery Ltd.
Waterside South
Lincoln LN5 7FD
United Kingdom
+44 1522 584000
welch.michael@siemens.com
brian.igoe@siemens.com

Mattias Samuelsson
Siemens Industrial Turbomachinery AB
Slottsvagen 2-6
Finspong
Sweden
+46 122 82731
mattias.samuelsson@siemens.com

ABSTRACT

Over the last 20 to 30 years environmental concerns over pollutants created during the combustion process have driven gas turbine manufacturers to develop combustion systems that create lower and lower emissions of nitrous oxides (NO_x), carbon monoxide (CO) and unburned hydrocarbons (UHC). To meet this challenge, manufacturers developed Dry Low Emissions (DLE) or Dry Low NO_x (DLN) combustion systems. Primarily employed initially in industrial applications or utility power plants using pipeline quality natural gas as the main fuel, DLE became quickly established and is now a well-proven technology with thousands of units installed and tens of millions of operating hours experience gained. Some manufacturers now only offer DLE combustion systems on some gas turbine models - such is the confidence in this technology.

However, for both environmental and economic reasons, operators have pushed for DLE combustion systems to be able to use gas fuels which lie outside the normal composition spectrum for natural gas. These gases may be rich or weak produced from industrial processes or by-products from oil production or gas processing, with a wide range of constituents and whose composition varies with time. The composition and variability of these gases creates challenges for DLE combustion systems, and in addition to inert gases, such as nitrogen or carbon dioxide, more reactive gaseous fuels such as ethane, propane along with those containing hydrogen and carbon monoxide can exacerbate operational issues such as “flashback” or instability.

In addition to reviewing the challenges of using these fuels, this paper describes the development and testing work undertaken by Siemens on the full industrial gas turbine product range, between 5MW and 50MW in power output in order to characterize the capabilities of the DLE system with respect to the wide range of gas fuel compositions which have been identified by a number of operators. Finally, the paper provides and discusses some examples of operating installations both industrial and Oil & Gas applications where non-standard and variable fuels are used whilst still meeting the required emission limits and without affecting operability.

1. INTRODUCTION

Gas fuels for gas turbines can come from a wide variety of sources. While the majority of gas turbines onshore operate on ‘pipeline quality’ gas which has been processed to meet a specific requirement set out by regulators and pipeline operators, many units offshore and in more remote oilfield locations operate on associated gas which can vary greatly in composition compared to pipeline quality natural gas. In addition there is the potential to use low cost 'opportunity fuels' such as by-products from gas processing, which may contain high levels of ethane and propane, or biogases which have a high inert gas content.

Modern highly efficient gas turbines rely on high-quality alloys to allow increased firing temperatures to be achieved, whilst still maintaining acceptable product life. To ensure this is achieved, far more attention to the use of the fluids entering the gas turbine is necessary, including air, lubricating oil and fuels. In this paper the use of fuels with high inert gas content is presented and discussed.

Fuels used in GT applications vary widely with the choice based typically on availability and cost. In some cases these gas fuels, particularly those with high inert gas contents, may require little or no treatment. Gas Turbines can, and do, operate on a wide range of fuels, but the impact that such fuels may have on turbine operation and component life has to be recognized and allowed for.

To achieve this, it is necessary to understand the details of these fuels, such as the composition, hydrocarbon species, inert species, contaminants and water vapor. Detailed analysis of the fuels is necessary to determine key parameters of the fuel, including Lower Heating Value, Wobbe Index, dew point and density. Understanding all of these provides the OEM and user with indicators confirming the fuel entering the GT is suitable for achieving good operation across a wide range of loads and ambient conditions.

It is also important to determine and understand the products of combustion and their impact on the environment. Exhaust emissions are highly regulated in many parts of the world and even those areas that up until recently had no requirements have started to introduce standards or guidelines which need to be noted during the assessment stage.

This paper looks at some of the development work carried out and the operational experience gained by Siemens on their light industrial gas turbine portfolio to enable operation on non-standard fuel gases, using models fitted with Dry Low Emissions combustion systems.

2. UNDERSTANDING WOBBE INDEX

Pipeline quality gas fuels generally contain methane, with small quantities of ethane, and for most OEMs fall into a Wobbe Index (WI) range 35 – 50MJ/m^3 (940 - 1340btu/scf).

Wobbe Index is one of the parameters used to assess fuels and allows a direct comparison of different fuels to be made based on heat content. WI is the net (lower) calorific value of the fuel divided by the square root of the fuels specific gravity.

WobbeIndex

$$WI^0 = CVv^0 / \sqrt{SG^0}$$

where CVv^0 = net calorific value (MJ/m^3) at standard conditions (288K, 1.013bara)

SG^0 = specific gravity at standard conditions = ρ_{fuel} / ρ_{air} where ρ_{fuel} and ρ_{air} are at standard conditions (288K, 1.013bara)

Fuels are often provided at different supply conditions. Therefore the use of Temperature Corrected Wobbe Index (TCWI) becomes an important aspect when reviewing fuels. Gas fuels containing water and or higher hydrocarbon species will result in higher dew point requirements, hence the need to provide a set amount of superheat margin, ensuring the gas remains in a vapour at all times.

$$WI^T = WI^0 \sqrt{288 / T_{fuel}}$$

Where:

T_{fuel} is temperature of fuel at turbine skid edge(K)

WI^T = Temperature Corrected Wobbe Index

WI^0 = Wobbe Index at Normal conditions, 288K

Fuels with visually different compositions may have the same Wobbe Index and therefore same heat content. However, other factors such as dew point and density need to be evaluated.

GT OEMs have limits on ranges of fuel calorific value or Wobbe Index before it becomes necessary to introduce changes in combustion hardware. This may be as simple as geometry changes within the same burner, or more extensive changes involving fuel system modifications, with the objective being to achieve a similar fuel supply pressure and pressure drop across the burner to ensure stable combustion is maintained.

Gas fuels with high inert contents will have a lower Wobbe Index compared to pipeline quality natural gas. As the proportion of inert gas content increases, then the Wobbe Index reduces, as shown in Figure 1 below, requiring higher fuel volumes to achieve the correct energy input. However, the hydrocarbon species present in the gas will also have an impact – a high inert content fuel gas will have a higher Wobbe Index if it has some higher hydrocarbon species such as ethane and propane present, than if the hydrocarbon species is solely methane. Conversely fuels made up predominantly of higher hydrocarbon species such as ethane and propane have a higher Wobbe Index than pipeline quality natural gas so a reduced fuel volume is required.

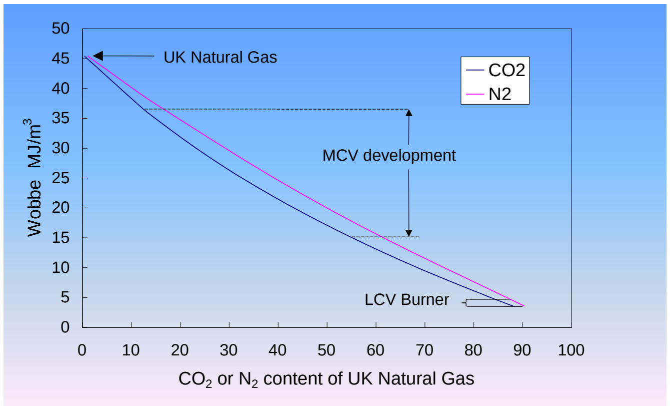


Figure 1: Impact of Inert Gas content on fuel Wobbe Index

3. GAS FUEL SYSTEM AND BURNERS

Whether the combustor is a diffusion flame design or Dry Low Emissions design, the first and major challenge is to be able to handle and inject the volume of fuel gas required to achieve the same energy content as a pipeline quality natural gas, and to ensure stable combustion. For a 'weak' gas with a high inert gas content, it may be possible to employ a standard burner configuration and gas fuel system by simply increasing the fuel supply pressure slightly to reduce the volume flow, or to increase the injector hole size, while for 'rich' gases with high hydrocarbon contents smaller injector hole sizes may be required.

As the inert gas content increases, an increasingly high gas supply pressure becomes necessary and eventually a pressure limit will be reached. It may therefore necessary to apply modified designs to accept higher inert gas contents.

Within the burner and fuel injector itself, it may be required to increase the gas gallery and injection port sizes to prevent too high a pressure drop across the burner. The necessary modifications to burners and fuel injectors will vary from gas turbine to gas turbine, depending on the burner design. For example, on the SGT-300 and SGT-400 gas turbines, three different burner designs are required to cover the Wobbe Index range from 15MJ/m^3 to 50MJ/m^3, whereas the SGT-700 and SGT-800 can cover almost the same Wobbe Index range within the standard burner design. In addition, no matter what the burner capability is, the fuel supply system will require larger diameter pipework and larger valves to handle the increased gas volume flow.

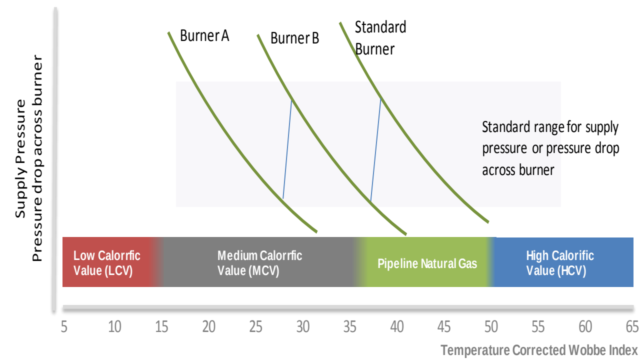


Figure 2: Illustration of Wobbe Index range for different burner injection port sizes

For gas fuels with a high Wobbe Index that may lie outside the capability of the fuel injector, there are two methods that can be employed to bring the fuel into a condition that allows it to be used without modifying the injectors. The first option is to heat the fuel to a higher temperature. This reduces the Wobbe Index, but care must be taken not to exceed the temperature limits of the fuel supply system (typically 120°C to 140°C). The second option is to create a fuel blend, either by mixing the high Wobbe Index fuel gas with a lower Wobbe Index gas, or by adding air or an inert gas to the high Wobbe Index gas.

Figure 3: Scaled DLE combustion can hardware showing family concept for various industrial gas turbine models

An additional challenge often found in Offshore applications is variability in the fuel gas composition. The burners, fuel system and control system must therefore be designed to operate across a range of Wobbe Indexes, and also be able to cope with changes in Wobbe Index during operation.

While care must be taken with all fuel gases to ensure that the supply temperature is sufficiently high to keep any water in the gas in the gaseous phase, for gases containing higher hydrocarbon species the supply temperature needs to be kept above the hydrocarbon dewpoint too to prevent condensation and uncontrolled combustion occurring. With gases containing propanes and heavier hydrocarbon compounds, the fuel gas should be reviewed to ensure auto-ignition is avoided: the high temperatures and pressures of the air coming off the gas turbine compressor may be sufficient to cause auto-ignition of the fuel within the injector.

In addition to the fuel system and fuel injectors, it should also be noted that non-standard fuel gases may require changes to the gas turbine package itself: hydrocarbons such as propane and butane are heavier than air, so unlike natural gas, will collect at a low level within the underbase in case of a leak. This requires gas detectors to be repositioned and the ventilation air flowpaths to be checked or recalculated to ensure an explosive mixture cannot form.

4. GAS TURBINE PERFORMANCE

It is important to recognise that the gas turbine performance is specific to composition and supply pressure for each proposed fuel gas.

A reduction in the Wobbe Index of the fuel results in an increased mass flow rate through the turbine. This increased flow rate can enable an enhanced power output to be developed for a given Turbine Entry Temperature (TET). However, not all the theoretical power enhancement can necessarily be achieved in reality.

The increased mass flow leads to increased local velocities within the turbine, influencing the heat transfer coefficients on the hot gas path components. With reduced cooling, the life of the hot gas path components would reduce, and so to maintain component life the same as for a pipeline quality natural gas, the TET may be reduced slightly compared to that on a standard gas fuel. While there is still a power enhancement by using high inert content gas fuels, this reduction in TET reduces the theoretical achievable power slightly. However, in almost all cases, using a fuel gas with high inert content improves power output and efficiency compared to operation on a pipeline quality natural gas, as can be seen in Figure 3 below.

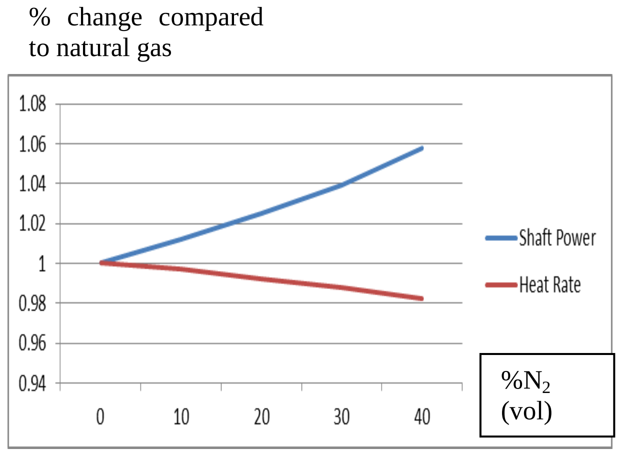


Figure 4: Variation in shaft output power and heat rate for an SGT-700 with increasing N_2 content in the fuel gas.

When operating with high volume of inert constituents in the fuel gas, increased work is performed by the turbine expanding the additional mass flow. This causes an increase in the compressor working line, and on aero-derivative gas turbines with multi-spool designs, this can vary between the HP and IP compressors. In order to maintain surge-free operation and sufficient over-speed margins for the power turbine, the transient load acceptance and shedding capability of the engine might be reduced.

Conversely with rich fuel gases, the higher energy content means that a lower fuel flow is required so the mass flow reduces slightly, with a potential minor negative impact on gas turbine performance.

When it comes to NO_x emissions, the composition of the gas can have a considerable impact, especially on a Dry Low Emissions (DLE) combustor. NO_x emissions from a gas turbine are predominantly caused by thermal NO_x which is dependent on the flame temperature and the peak temperatures within the flame. Simplistically, for weak gases with a high inert content, the inert gases act as a diluent and 'cool' the flame, reducing NO_x slightly, whereas for rich gases with significant higher hydrocarbon contents, the longer hydrocarbon chains burn with a higher flame temperature, increasing the NO_x emissions compared to 'pipeline quality' natural gas.

5. GAS TURBINE STARTING

Starting a gas turbine on a high inert content fuel gas can be problematic. In addition to ignition, the turbine must also be able to accelerate to no-load speed without experiencing flame-out. This requires maintaining sufficient fuel flow to provide sufficient heat input to sustain stable combustion. This may require changes to the normal start procedure, such as reduced speed when attempting ignition, changes to purge times and ramp rates, and changes to fuel scheduling.

Siemens have undertaken considerable work on the different turbines within its portfolio to resolve this issue, which is discussed in more detail in later sections.

In the worst case scenario, starting may have to be achieved using a secondary fuel, such as diesel, or by enriching the fuel gas by adding natural gas or propane for example.

6. TESTING AND OPERATIONAL EXPERIENCE

Siemens has developed and proven the capability to operate on both high inert and high hydrocarbon content fuels on a number of its gas turbines, especially in DLE combustors. Successful operation has been achieved on fuels with up to 50% N_2 or 40% CO_2, and on gases where the CO_2 content has varied between 2% and 25%, and on fuels containing up to 100% propane. The following sections look in a little more detail at some of the testing and operational experience gained on various gas turbine models.

6.1 SGT-300 / SGT-400

For the SGT-300 and SGT-400 gas turbines, significant testing, including HP rig testing, was done on single Dry Low Emissions burners with larger gas injection ports than a burner using a standard gas fuel to map the capability of individual burner designs. This testing confirmed that two burner variants could cover the Temperature Corrected Wobbe Index range from 17.5MJ/m^3 through t to 49MJ/m^3. The lower limit for each burner range is dictated by supply pressure constraints as well as pressure drop across the burner in order to maintain optimum combustion and avoid issues around flashback and blow-off, or excessive CO emissions). This rig testing was then confirmed by results achieved on operational units, and on contract specific full engine tests.

One of the first units to operate on a high inert gas was an SGT-300 with a DLE combustion system installed at the University of New Hampshire, USA. The primary fuel, a processed landfill gas (PLG), typically had a maximum inert gas contente of 25% (vol) with a WI of circa 28-34MJ/m^3, and a minimum set point for operation set at 32MJ/m^3. When the WI dropped below 32MJ/m^3, or was insufficient quantity for the GT duty, pipeline quality gas was blended as required. In addition, the SGT-300 was also required to be able to operate on 100% pipeline quality natural gas and diesel as back-up fuels. For gas fuel operation, the same fuel passages were used in the burner, giving it an operational range of betwen 32 and 49MJ/Nm^3. Further factory testing demonstrated that this burner design when combined with a new gas fuel control valve could actually operate down to 30MJ/Nm^3.

Figure 5: SGT-300 at University of New Hampshire, operating on a processed Landfill Gas

This was swiftly followed by some SGT-400 projects, all using the Dry Low Emissions combustor design which is standard on the SGT-400. The first two projects were for Oil & Gas applications on gas fuels with Wobbe Index of circa 27MJ/m^3 (offshore platform – weak wellhead gas) and 34MJ/m^3 (onshore - weak wellhead gas), both of which have been operating satisfactorily for some years. More recently experience has been gained on an SGT-400 on a 22MJ/m^3 fuel gas with up to 40% CO_2, (biogas from Ethanol Industry waste). This installation is a ‘gas only’ configuration with both start-up and transient operation, as well as full load operation, proven on this weak biogas. The most recent order has been for two SGT-400 generator sets for an offshore platform in South-East Asia where the units are required to operate on two separate potential fuel gas streams, one a relatively ‘standard’ gas with 2% CO_2 and the other a weak gas containing 25% CO_2. Both gases, or blends of the two gases, use the same full passages in the burner. Full customer-witnessed engine testing using LNG doped with N_2 to simulate the contract fuels demonstrated the ability of the SGT-400 to start up and operate on either fuel, and switch between fuels while maintaining stable operation, without exceeding the guaranteed emissions of 25 ppmv NO_x.

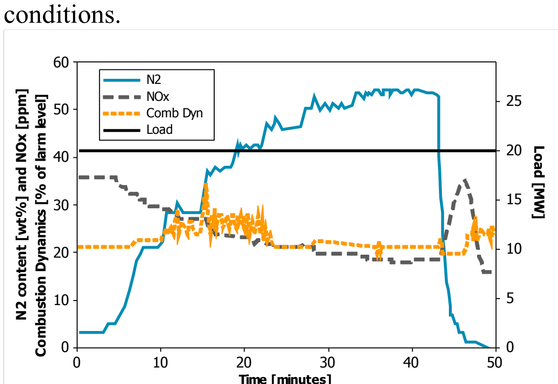
Figure 6: SGT-400 Generator Set modules for an Offshore Platform, South-East Asia, configured to run on two different fuel gases, one with a high CO_2 content

6.2 SGT-700 / SGT-800

The fuel flexibility of the SGT-700 and SGT-800 gas turbines has gradually been extended, starting out with single burner tests at atmospheric as well as pressurized conditions, and continuing to full-scale tests. More recently tests have been carried out during the works test of a standard turbine, or in an actual gas turbine installation in Sweden, by using a separate feed of test fuel to one or more burners, while the remaining burners continue to use a standard gas fuel.

Despite being fitted with Dry Low Emissions burners, no hardware modifications were made to the turbines, but the control systems were adjusted to allow for the higher volumetric fuel flows.

Tests were carried out on the SGT-700 to 40% N_2 by weight and up to 50% by volume on the SGT-800. The inert gas content was gradually increased during testing of the units, and in both cases no influence from the nitrogen content in the fuel was seen with respect to combustion dynamics. The engine tests also showed NO_x emissions decreasing as N_2 levels increased under various load conditions.



Figures 7 and 8: Measurements from SGT-700 Gas Turbine test with N_2 blending, and a photograph of the gas blending system in operation

As can be seen in Figure 7 above, the N_2 content in the fuel gas on the SGT-700 turbine test reduced from 40% by weight to zero over a period of 2 minutes. This rapid change in Wobbe Index had no impact on gas turbine operations.

Following successful testing on high inert gas fuels, both the SGT-700 and SGT-800 have been sold for high inert gas fuel applications. Two SGT-700s were sold to Linde to drive the Boil-Off Gas compressors at Malaysia LNG, where the fuel gas could contain up to 40% N_2 by volume, while two SGT-800 units will be installed in 2015 in Poland to run on a fuel gas containing 50% N_2 by volume.

On the 'rich' gas spectrum, an SGT-600 with a previous generation of DLE combustor design had operated on 100% propane for around 10,000 hours in the mid-90s. This experience was used to help develop 100% ethane and 100% propane capability on the SGT-700 in the next generation of DLE combustors – known internally as the 3rd Generation DLE burner.

Figure 9: 3rd Generation DLE burner as used on the SGT-700 and SGT-800 Gas Turbines.

Following the works acceptance test on 100% ethane, an SGT-700 was sold to a Propane dehydrogenation PDH plant in China to operate on an ethane-rich process off-gas. PDH is a process step in the production of propylene from propane. PDH is vital to the petrochemical industry: propylene is the second most important starting product in the petrochemical industry after ethylene. Propylene is the raw material for plastic polypropylene, which is a common component mainly used in the automotive and textile industries, for plastic films for packaging and many other products. This gas turbine was commissioned using propane as the main fuel as this was readily available as the main feedstock for the PDH process, and is also used as the start-up fuel. During normal operation however, the gas turbine operates off the de-ethanizer off-gas, which is variable in composition, and is often combined with propane or even heavier fuel streams. The SGT-700 has demonstrated stable operation even on this highly variable composition fuel, some examples of which are shown in Figure 10 below. All fuel sources use the same fuel passages within the burner and a common fuel delivery system.

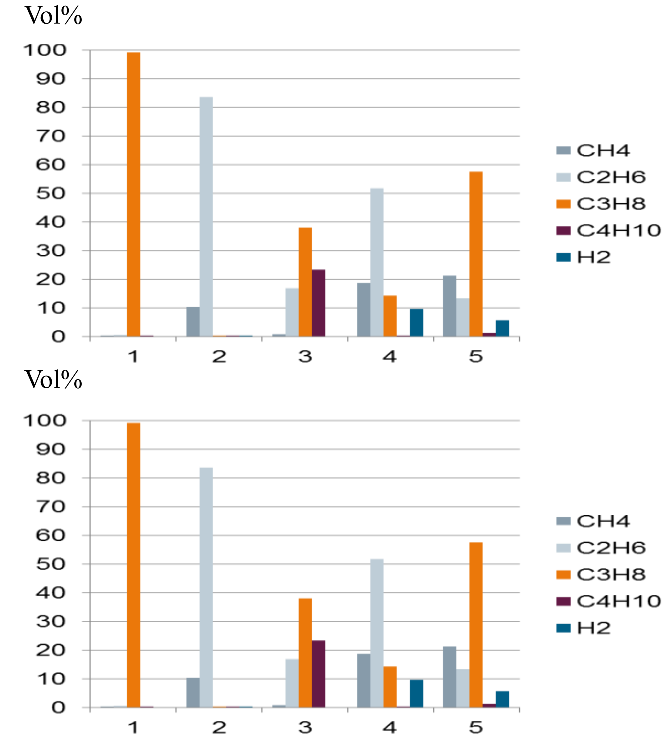


Figure 10: Snapshots of some of the fuel compositions seen by the SGT-700 gas turbine in a PDH plant in China

Testing has also demonstrated the ability to operate on pentane-enriched natural gas, further expanding the range of fuels that can be considered suitable.

7. HYDROGEN

There is increasing interest in using hydrogen as an energy storage medium to capture surplus renewable power. The concept is excess solar or wind energy is used to create hydrogen from water using electrolysis, and the hydrogen can either be fed up to a certain percentage into the natural gas transmission system or burned in a gas turbine to generate power when the intermittent renewable power generation sources are not available.

Hydrogen-rich fuels particularly give rise to flashback concerns due to the high flame speed of hydrogen. High hydrogen operating experience in gas turbines has predominantly been gained using diffusion flame combustion systems.

During engine testing in 2012 on the SGT-700 featuring a 3rd generation DLE system, hydrogen-enriched natural gas operation was verified. This enabled a general release for the 3rd generation DLE system of up to 15% H_2 by volume to be permitted, with the possibility to accept higher fractions on a case by case basis.

Further analysis of the 2012 hydrogen tests indicated that minor modifications to the standard burner could improve hydrogen capability. Further tests in 2014 using a modified burner confirmed the possibility to operate an SGT-700 on 40% H2 by volume at high turbine loads, while at low loads even higher hydrogen volumes could be accepted. This modified burner is also able to operate on 100% natural gas with acceptable emissions, as well as maintaining the weak and rich gas capability. Thus it has been demonstrated that for the 3rd Generation DLE combustor, the acceptable Wobbe Index ranges from 25 to 80MJ/Nm^3 without modifications to the burner hardware.

	Maximum H_2 (% vol)	Additional comments
SGT-100	5	Standard natural gas burner
SGT-200	5	Standard natural gas burner
SGT-300	5	Standard natural gas burner
SGT-400	5	Standard natural gas burner
SGT-500	n/a	
SGT-600	15	up to 40% H_2 (vol) + methane mix available soon
SGT-700	15	up to 40% H_2 (vol) + methane mix available soon
SGT-750	n/a	
SGT-800	15	up to 40% H_2 (vol) + methane mix available soon

Figure 11: Hydrogen capability of the Siemens Industrial Gas Turbine range in a DLE combustor

8. GAS TREATMENT

In extreme cases, the inert gas content in the fuel gas may exceed the current design capabilities of the gas turbines. It may be possible under future development projects to further increase the permissible inert gas content beyond the current 50% (vol) N_2 and 40% (vol) CO_2 demonstrated on some gas turbine models.

For current projects however, for inert gas contents above demonstrated limits, it is necessary to process the fuel gas using a proprietary technology to reduce the inert gas content to an acceptable level. Technologies such as membrane removal systems, pressure swing adsorption systems or amine scrubbers have been commonly employed in the Oil & Gas industry to provide suitable treatment of gas streams.

For 'rich' gases, where it is not possible to create a suitable fuel gas by blending or heating as described in section 3, it is necessary to remove the longer hydrocarbon chain components of the gas stream. This is usually achieved using cryogenic processes to cool the gas to below the condensation temperature of the heavier hydrocarbons, allowing them to be removed as liquids.

CONCLUSIONS

Operation of the DLE burner on a wide range of variable fuel gases has been proven without the need to add additional passages within the burner itself.

The use of fuel gases with high inert gas contents in DLE combustion systems has been proven on gas turbines across the product range on fuels with up to 40%

CO_2 or 50% N_2 content, with Siemens' models having gained many thousands of hours' operational experience. It has also been proven that these fuels can also be used in Dry Low Emissions combustors with no detrimental effect on operability, even though the inert gas content may vary, with no need for external instrumentation to measure fuel gas composition or calculate the Wobbe Index.

Additionally operation on heavier hydrocarbon fuel gases has also been demonstrated in the 3rd generation DLE combustors installed on the SGT-700 and SGT-800, with the ability to operate on 100% propane proven, with no burner modifications required, enabling a single burner design to accept a Wobbe Index range from 25 to 80MJ/Nm^3. This burner design has also demonstrated a capability to accept high concentrations of hydrogen in a methane/hydrogen blend.

ACKNOWLEDGEMENTS

The authors would like to thank their colleagues in Finspong, Sweden, especially Jenny Larfeldt and Anders Larsson.

REFERENCES

1. Igoe Brian, Stocker Andrew, Siemens Industrial Turbomachinery Ltd., UK
Extended Fuels Capability of Siemens SGT-400 DLE Combustion System, IDGTE 2014, UK

2. Larfeldt Jenny, Larsson Anders, Anderson Mats, Siemens Industrial Turbomachinery AB, Sweden, SGT-700 and SGT-800 Fuel Flexibility Testing Activities, The Future of Gas Turbine Technology 6th International Conference, Brussels, 2012

3. Igoe Brian, Welch Michael, Siemens Industrial Turbomachinery Ltd., UK, Gas Fuel Flexibility in Dry Low Emissions Combustion Systems, 9th Forum de Turbomaquinas Petrobras, Rio de Janeiro, 2013

4. Welch, Michael, Igoe Brian, Siemens Industrial Turbomachinery Ltd., UK, Impact of Carbon Dioxide and Nitrogen in Fuel Gas on Gas Turbine Operation, OTC-26347, OTC Brasil, 2015, Rio de Janeiro

5. Bonaldo Alessio, Andersson Mats, Larsson Anders, Siemens Industrial Turbomachinery AB, Sweden, Engine Testing Using Highly Reactive Fuels on Siemens Industrial Gas Turbines, GT2014-26023, ASME Turbo Expo 2014, Dusseldorf, Germany

6. Larsson Anders, Andersson Mats, Manrique Carrera Arturo, Blomstedt Mats, Siemens Industrial Turbomachinery AB, Sweden, Extended Fuel Flexibility Capabilities of e SGT-700 DLE Combustion System, 2015 IAGT, Banff, Canada