Dry Low Emissions Experience across the range of Siemens Small Industrial Gas Turbines

BM Igoe
Product Manager SGT-100/SGT-200
Siemens Industrial Turbomachinery Limited, UK

In the 15 years since Siemens Industrial Turbomachinery Limited (SITL) introduced a Dry Low Emissions combustion system across the small gas turbine product range, in excess of 7.5 million operating hours have been accumulated across a wide variety of duties and locations. Initial applications addressed land-based power generation requirements where lower legislated NOx requirements were identified. Applications for onshore and offshore mechanical drive and power generation duty followed with low emissions driven by legislative means as well as customer focus.

Low Emissions operation was initially aimed at high loads and capitalized on the benefits from lean pre-mixed combustion in terms of very low NOx and CO exhaust signatures. More recently there has been a drive to achieve acceptable emissions over a much wider operating range of loads, typical of a gas turbine driving a pipeline compressor. Therefore, additional research and development activity has been carried out to ensure low emissions of both NOx and CO are maintained over as wide a load range as possible.

This paper describes several of the activities completed over the years to keep the DLE capability on the Siemens SITL product range at the forefront of technology. Also provided is an overview of the development of this unique combustion system along with the breadth of operating experience. Operational issues are described, as is the method used to resolve such issues, proving the robustness of the DLE combustion system. One area discussed is the need to provide and maintain good quality control with regard to gas turbine fuels to avoid compromising turbine life and operation.
Introduction
In excess of 7.5 million operating hours have been accumulated across a wide variety of duties and locations using dry low emissions combustion system in the range of small gas turbines produced in the Siemens facility in Lincoln, UK. Initially, applications addressed land-based power generation requirements where lower legislated NOx requirements were identified. The first of these was located in The Netherlands and continues to operate today, having achieved the notable milestone of 100,000 operating hours. Applications for onshore and offshore mechanical drive and power generation duty followed with low emissions driven primarily by customer focus but also by the extension of lower exhaust emissions to new offshore projects.

Aimed primarily at high loads, the benefits from lean pre-mixed combustion in terms of very low NOx and CO exhaust signatures were easily achieved and recognized. Now the drive is to achieve both low and acceptable emissions over a wider operating range of loads, for example those applications typical of a gas turbine driving a pipeline compressor. To achieve these increased demands, the use of more sophisticated controls was necessary with regard to air and fuel management.

Over recent years, many incremental improvements have been developed and implemented in order to keep the DLE capability on the Siemens SITL product range at the forefront of technology. In addition, relevant experience for this combustion system is detailed along with the breadth of operating experience including some operational issues, along with methods used to resolve such issues, proving the robustness of the DLE combustion system. One such area discussed is the need to provide and maintain good quality control with regard to gas turbine fuels to avoid compromising turbine life and operation. This latter subject is a major topic in its own right and cannot be given full justice in this paper.

Combustion system available
Two major types of combustion system are available on the Siemens, SITL (SITL) products, one based on diffusion flame and the second using lean pre-mix technology targeting low exhaust emissions signature.

Diffusion flame operates at high primary zone temperature, circa 2500K, which results in high thermal NOx formation. Reduction of the flame temperature results in lower NOx formation. With diffusion flame this can be achieved by injection of diluents such as water or steam into the primary zone. This has been successfully employed over many years across the product range (excepting the SGT-400, which is DLE-configuration only).

The modern approach now is to achieve the lowering of primary zone temperatures without resorting to wet diluents. Dry Low Emissions (DLE) combustion systems address the production of NOx at source with a design that does not rely on injected diluents, hence the term “dry”. Of the different types of dry combustion, namely lean premix, staged and catalytic combustion, the lean premixed system has been developed by SITL as the combustion system of choice with many millions of operating hours recorded. Lower NOx formation has been achieved by combusting in an excess of air. NOx production increases exponentially with temperature, therefore it is critical to ensure air and fuel are well mixed. During the early design and development work, there was as much attention devoted to achieving a homogeneous mixture, as to burning this mixture, without detrimental impact on combustion and turbine hardware.
Drivers for low emissions
Legislation, OEM and Customer Low Emission Requirements
The US Clean Air Act set new standards for emissions compliance, which included stationary power plants where gas turbines were included. Therefore, in the last 25 years, increasing pressure was placed on the gas turbine OEM’s to develop less polluting products. The European Union (EU) and other countries soon followed with more demanding legislative requirements, thus low emissions became the norm and not the exception.

In addition, the major gas turbine OEM’s, along with a large number of major Oil & Gas companies, have their own policies with regard to the environment and will offer or specify low emission equipment even in applications where no formal legislation exists, or is set at a higher level.

The result of all of these drivers is to make the SITL DLE combustion system the major combustion system of choice. The most recent product in the portfolio, SGT-400, comes with a DLE combustion system as standard. Even with the SGT-300, the number of non-DLE (diffusion flame combustion) is in a minority (accounting for no more than 15% of total SGT-300 fleet).

Experience of SITL
Across product range
The SITL DLE combustion system is a generic design fitting the cannular design philosophy of the product portfolio. Initially validated on the SGT-100 (when this product was named “Typhoon”), it is available on all of the products from the SGT-100 through to the SGT-400. The major design differences between the engines were met by mechanical scaling, or adapting common designs to accommodate increased mass flow. Both the SGT-100 and SGT-200 share many common components, the latter requiring eight burners and combustors to the SGT-100 requirement for six of each

Figure 1: DLE Combustor – Main components
**Combustion Design Features**
The SITL DLE combustion system comprises the following main elements as shown in figure 1:
- Pilot burner
- Main burner (includes radial swirler)
- Gas/liquid core
- Impingement-cooled combustor
- Transition duct

The pilot burner face is metal-sprayed to afford better protection against oxidation. It is located slightly back from the gas-washed surface of the swirler to aid stability. Each burner contains its own ignition source.

**Range of duties**
Onshore power generation applications dominated early DLE experience, especially in CoGen or CHP application. Once the technology was shown to be fully commercial, some Oil and Gas companies looked to DLE as a viable solution for both power generation and mechanical drive applications both onshore and offshore.

Numerous applications today offer solutions to the pipeline compressor market, where part load duty appears to be the norm. Therefore, the ability to operate over a wide range of loads and ambient conditions is vitally important.

**Load and ambient conditions**
Activities associated with the development of the SITL DLE combustion system had some limitations. For example, the high-pressure combustion rig development facility was located where the range of ambient temperatures was limited (temperate). Ambient extremes associated with cold winters (artic) or hot deserts were not able to be fully demonstrated, although the high-pressure combustion rigs were able to simulate aspects of engine duty under different ambient conditions.

Lean pre-mix combustion systems are inherently weak under low or part-load operation, especially in a single-shaft (constant speed) gas-turbine configuration. This weakness is due to the increased “leaning” out of the fuel-air mixture, resulting in a rapid increase in CO-formation, and as a consequence stability issues are of increasing concern. Improvements in air management through control of the compressor variable guide vane (VGV) position (single shaft) and P2 bleed system (twin shaft) are discussed later as a means of improving the stability margin. These techniques effectively richen the combustion fuel-air mixture; hence maintain acceptable levels of exhaust pollutants over a wide range of loads.

**Major features**
All products in the SITL portfolio have a common approach to combustion and use a number of reverse-flow tubular combustion chambers positioned around a high-pressure casing. Each is capable of gas-only, liquid-only or dual-fuel operation. Fuel is controlled by both a pilot and main burner, with the control system providing for smooth changeover across the power range.

In the case of the SGT-100, SGT-300 and SGT-400 there are six reverse flow combustors, whilst the SGT-200 has eight, and are of a common design with the SGT-100 (sharing the same burner). Materials used throughout the combustion system are conventional, based on stainless steels, with use of nickel-based alloys limited to the combustor and transition ducts.
NOx exhaust emissions can be reduced by using lean well-mixed combustor primary zone, with the extent of reduction closely linked to the mixing quality of air and fuel. In the case of SITL this has been achieved through the use of radial swirler passages and multiple fuel-injection points as a means of partially pre-mixing fuel and air.

The use of fixed geometry of the radial swirler means the control of fuel, and impact on NOx formation is controlled by the amount of pilot flow applied, especially at the higher loads. The pilot flow is also used to maintain a degree of stability, allowing for instant and automatic load rejection and re-application to be made without affecting turbine operation such as flame failure and engine shutdown. To ensure acceptable operation, achieving both low NOx and CO emissions, it is necessary to accept a compromise between NOx and CO, figure 2. Increasing flame temperature allows more complete combustion of CO, but at the expense of higher thermal NOx formation. Conversely, increasing the amount of air (i.e. leaning out) reduces NOx, but with increased instability and high levels of CO emissions

**Wider operating range**

Although initially limited to a range of power, 70 – 100% load, and ambient temperatures, -20/+40°C, the SITL DLE combustion system has operated for long periods at both lower loads and at extremes of ambient temperatures, such as those in arctic or desert conditions. As a result of this experience, changes to the DLE operating envelope have been introduced.

**VGV and P2 bleed controls**

As mentioned earlier, a poor feature of a lean pre-mixed combustion system is operability at lower loads. At a constant mass flow (as found in a single-shaft turbine), part-load operation results in even leaner air fuel mixtures. This results in stability concerns, impacting the emissions of carbon monoxide, CO. As CO-formation is controlled by operating temperature, one of the simplest methods of ensuring acceptable combustor temperatures is to reduce the amount of air passing through the combustor. This can be achieved in two ways. On single-shaft turbines, such as those typically used for power generation, closure of the compressor variable guide vanes (VGV) ensures reduced mass flow to the combustor and hence higher flame temperatures and combustion efficiency.
Where even lower load operation is required, or for mechanical drive duty (two-shaft configuration) some of the air can be bled before it enters the combustion system. This is known as P2 bleed. The bleed air is either returned directly into the exhaust, or, to minimize the impact on overall turbine efficiency, returned to the intake of the gas turbine, figures 3 & 4.

These methods of additional control allow acceptable exhaust emissions to be achieved at lower operating loads. 50% load or lower are possible, however, it must be recognized that other turbine limitations then start to contribute to the overall operating envelope. Limits on exhaust temperatures are specified according to materials typically used such as those used in the exhaust. Similarly compressor limits need to be applied such as pressure ratio control, to prevent compressor surging, as well as possible effects of reduced cooling to the hot turbine blades. These and other factors need to be considered and assessed when defining the emissions operating envelope at lower loads and extremes of ambient temperatures.

Both these methods of air management have similar effects in elevating the combustion temperatures to that associated with operation at higher loads (subject to the other limits, some of which were mentioned earlier). The result is acceptable levels of exhaust emissions, especially carbon monoxide, without impact on NOx production.

**Improvements**

Since the introduction of the SITL DLE combustion system, a number of improvements have been introduced, targeting increased fuel flexibility as well as ensuring the emission signature from the product achieves both customer and legislative needs. Some examples of the significant ones are shown below.

**SGT-400 Expanded Fuel Capability**

The SGT-400 is configured with a lean pre-mixed DLE combustion system only and operates over a range of gaseous fuels of Wobbe Index (WI) = 37 - 49 MJ/m$^3$ (810/1100 BTU/Scf), where:

\[
WI = \frac{LCV}{SG}
\]

\[
CV = \text{net calorific value (MJ/m}^3\text{) at standard conditions}
\]

\[
SG = \text{specific gravity at standard conditions}
\]

\[
= \frac{\rho_{\text{fuel}}}{\rho_{\text{air}}}
\]

Standard conditions = 288K, 1.013bara
A number of gaseous fuels with lower WI have been encountered over recent years, especially in oil and gas applications, where increased level of inert species such as carbon dioxide (CO$_2$) and/or nitrogen (N$_2$) is a common feature. One solution to use such fuels is to remove, for example, CO$_2$ from the raw fuel, thus providing a more acceptable fuel for use in the current combustion hardware design. Although the additional processing is well proven, it adds unnecessary complication and cost to a power generation or mechanical drive plant and, equally as important, a weight penalty for offshore platform applications.

Siemens, SITL’s approach to the problem was to take the existing DLE combustion system and modify it through both analytical and practical means to achieve a solution which could be applied to a range of gaseous fuels in the WI range 15-49 MJ/m$^3$ figure 5. To date, validation of design changes to the burner resulted in release of a capability covering a range down to 25 MJ/m$^3$ across the full operational range of load and temperature. Throughout all of this work no increase in the current emission guarantee or turndown capability would be accepted.

The first contract covering such a medium calorific value (MCV) fuel application was offshore, Southeast Asia. The core engine was assembled and tested on natural gas with standard burner hardware and converted to the MCV build to use contract fuel of WI = 28 MJ/m$^3$, figures 6. As part of a package test, a full set of ignition tests was completed using bottled gas manufactured to simulate the contract gas specification. Successfully completed, this test included a demonstration to the customer, resulting in full release of this gas-only MCV configuration. This expanded fuels range has been applied successfully to other applications.

Improved Emissions Signature
This product has already demonstrated satisfactory exhaust emissions characteristic with normal operation of <25ppm NO$_x$ (corrected to 15% O$_2$) and including <10ppm NO$_x$ (corrected to 15% O$_2$) for some specific applications. However, the operability range for the lower level has been...
limited. Completion of additional development has resulted in a wider general operating range for both NO\textsubscript{x} and CO emissions. The range now available shows a reduction in general NO\textsubscript{x} signature from 25ppm to 15ppm, with 10ppm range at full load still available, where required.

Part-load CO-emissions control has become a bigger requirement and control of CO emissions to <50% load has been achieved and released by the use of a P2 bleed system (common feature with engine load shed control). This was described, above, in more detail.

**Issues**

**Combustion dynamics SGT-200**

Early DLE operating experience on the SGT-200 (Tornado) was very good, with no issues such as combustion dynamics recorded. However, commencing in 2003, a number of new engines exhibited combustion dynamics, predominately at very high loads (>95%). This was investigated and a solution determined and implemented, but in the interim period, a load limit of 95% was imposed.

Investigation of the issue followed a standard, but comprehensive, Siemens procedure in identifying and resolving issues. The Product Improvement Process, PIP, comprises eight steps, commencing with problem identification, going through a measure phase and onto root cause review. At this time, potential solutions are determined and evaluated, and the best solution implemented.

In this example the measure phase also included a Black Belt project within a Six-Sigma framework and identified a root cause resulting from a small change to the combustor-cooling geometry arrangement. The design of the combustor uses a double liner tube with a series of holes applied to both the inner and outer liners. Control of the holes sizes is critical to ensuring correct cooling as well as control of combustion vibration (dynamics). Controlling hole-geometry in achieving nominal to largest tolerance size had the desired effect of eliminating combustion dynamics and restoring acceptable operation (but leaving the holes too small made the vibration worse).

**Fuel Quality**

Modern highly efficient gas turbines rely on modern 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 on the use of the fluids entering the gas turbine is necessary, including air, lube oil and fuels. This section briefly covers some aspects of fuel quality and in particular gaseous and distillate fuel quality.

The subject of fuel quality is a major topic in its own right and cannot be done justice in this paper. Some of the fundamental requirements associated with fuel quality are discussed, along with potential issues associated with poor fuel quality.

SITL in common with other parts of Siemens, and other OEM’s, provide comprehensive specifications to cover the quality of fuel permitted for use in the gas turbine. These are used to ensure fuel quality is defined at the onset of a project and throughout the lifetime of the turbine and are prepared for good reason. To ensure acceptable life is achieved is seen as particularly important, with little or no impact on major turbine component life. Identification of contamination has become particularly necessary as this can have a detrimental impact on the exotic materials used in turbine blading. For example, the presence of hydrogen sulfide in the presence of sodium or potassium and water may result in sulfate formation, which is highly corrosive to the material used in the turbine blades.
The choice of gaseous fuels as a primary fuel for use in gas turbines is dictated by widespread availability and low price. Compositions of gaseous fuels can vary quite widely, from those taken directly from wells which can contain high amounts of heavier hydrocarbons, to those containing non-combustible species (such as nitrogen, carbon dioxide, argon ..) In some cases quantities of hydrogen sulfide may be present, which, left untreated, can produce sulfur oxides in the exhaust, and, more significantly, can combine with halides to form compounds which readily attack the exotic alloys used in turbine blading, resulting in premature component failure.

Gaseous fuels can contain contaminants from a variety of sources such as:

- Solids
- Water
- Higher hydrocarbons
- Hydrogen sulfide
- Carbon dioxide
- Carbon monoxide
- Hydrogen

It is important to provide the OEM with a comprehensive gas composition in order to determine the suitability of such fuels. Issues can be identified at this early stage to allow preventative measures, such as fuel treatment, to be taken.

Higher hydrocarbons influence the hydrocarbon dew point, hence high supply temperature is required. If the temperature is not maintained then liquid dropout will result and can cause problems in the fuel system, or, more seriously, impinge on combustor surfaces leading to localized burning and component failure, figure 7, which occurred very rapidly and resulted in engine shutdown.

Hydrogen sulfide combustion results in sulfur oxides in the exhaust (hence potential for acid rain). Of greater concern is the presence of halides, such as sodium and potassium, and water vapor. This results in the formation of alkali sulfates, giving rise to aggressive corrosion attack of the nickel alloys used in modern turbine blades, figure 8. This example is after several thousands of operating hours.

**Fuel requirements**

**Reasons for control**

Control of gas fuel quality for acceptable temperature is necessary. Gas dewpoint and superheat margin (SITL require +20degC superheat margin) ensures the effects of water vapor and higher hydrocarbon are fully assessed. If the temperature required is shown to be on the high side then trace heating and lagging become mandatory requirements. There is a maximum limit to the gas
fuel supply temperature, which is usually limited by components and materials used in the fuel delivery system.

**Issues resulting from poor fuel**

The table below identifies some of the issues resulting from poor or inferior fuel quality (this is a far from comprehensive list). In all respects there is an impact on gas turbine operation from issues within the delivery system, through to combustion issues that have the potential for premature failure of the combustor or even turbine blading.

<table>
<thead>
<tr>
<th>Operational concern</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Solids in gas fuel</strong></td>
<td>Wear of fuel system component</td>
</tr>
<tr>
<td>Scale, rust, sand, dirt, weld splatter, grit blast</td>
<td>Valve failure to seat increased leakage</td>
</tr>
<tr>
<td>From old poorly maintained pipe system</td>
<td>Corrosion and wear of fuel injector</td>
</tr>
<tr>
<td>From new or modified fuel system</td>
<td>Erosion of fuel/combustion components</td>
</tr>
<tr>
<td></td>
<td>Build up of debris in gas passageways - impaired operation</td>
</tr>
<tr>
<td><strong>Heavy Hydrocarbons as liquids</strong></td>
<td>Can drop out in fuel system, resulting in poor fuel control</td>
</tr>
<tr>
<td>Incorrect process control</td>
<td>Carried in combustion resulting in uncontrolled combustion - explosions, flashback</td>
</tr>
<tr>
<td>Not present in pipeline quality gases</td>
<td>Abnormal distribution and localised hot gas path component damage</td>
</tr>
<tr>
<td>Incorrect temperature for fuel dew point</td>
<td>Coking of fuel burner passages and mal distribution</td>
</tr>
<tr>
<td>Over fuelling (uncontrolled)</td>
<td>Abnormal temperature spread, as seen in exhaust / interduct thermocouples</td>
</tr>
<tr>
<td></td>
<td>Adverse impact on performance and emission targets</td>
</tr>
<tr>
<td><strong>Water in gas fuel</strong></td>
<td>Ice &amp; Hydrates can cause valve failure</td>
</tr>
<tr>
<td>Affinity of other contaminant - eg sodium, calcium etc</td>
<td>Corrosion of pipe system and valve</td>
</tr>
<tr>
<td>Formation of Hydrates</td>
<td>Corrosion of hot turbine components</td>
</tr>
<tr>
<td>At low temperature can freeze resulting in pipe blockage and reduced gas flow</td>
<td>Poor combustion operation, including loss of flame</td>
</tr>
<tr>
<td>ingestion of liquids into combustion with consequential damage</td>
<td>Unstable operation</td>
</tr>
</tbody>
</table>

Discussion so far has shown potential issues though poor-quality gaseous fuels. The same equally applies to distillate fuels. Significant differences in liquid-fuel quality exist throughout the world, and this has led to both handling and operation concerns. The handling of fuels from receipt, through storage and delivery to the turbine is equally important as the use in the turbine. It is not sufficient to agree the fuel specification suitable for use in the turbine if the method of handling and storage is inadequate. This will result in an inferior or contaminated fuel being supplied to the turbine.

Some of the commonest concerns include sourcing of the diesel fuel, supply (tanker) to the location, storage in suitable vessels, and ensuring the delivery to the turbine is acceptable. For example, the use of mild steel pipes and tanks in hot, humid environments could result in the fuel being contaminated with rust and scale, some of which would not be removed during filtration. This could result in issues in the turbine fuel system as well as changing, through nozzle blockage, the fuel injection profile to the combustor. A change in pattern (injection profile from the burner injection point) may result in fuel impingement on combustor surfaces or, in an extreme condition, destroy the pattern completely, resulting in a hot core and localized damage to turbine nozzles.

Storage of fuel is another area where issues may occur, especially if the use of distillate fuel is intermittent. Distillate fuels degrade and storage vessels can build up with sludge-like residue. The use of floating suction is one way in which the impact of this is minimized; coalescing filters or centrifugal device are other methods to ensure a more suitable delivery to the gas turbine.
A further area associated with poor fuel quality is contamination with water, and in offshore applications this tends to be sea water. Contamination with sodium and potassium can result in the production of compounds that are highly corrosive to the nickel-based alloys used in modern gas turbines. In some ways this is similar to the case of hydrogen sulfide present in gaseous fuels (sour gas), figure 8 above.

Summary

This paper provides an overview of the Siemens SITL Dry Low Emissions combustion system as applied to the SGT-100 to SGT-400 product range. Extensive operation with this system has been accumulated in the 15 years it has been in commercial use. Throughout this time, incremental improvements have been validated and introduced in order to expand the range of fuels covered as well as lowering base NOx emissions. Millions of hours of good operation have been achieved, although some issues have been identified over the years. Some of these are associated with design or manufacturing and have been addressed, but some are associated with fuel handing and supply and may require a change in mindset by owners and operators. Modern, highly efficient, gas turbines are more susceptible to variations in fuel quality, therefore it is imperative the gas turbine OEM fuel specifications are used not just at the tendering stage of a project, but throughout the lifetime of an installation. Good housekeeping is just as important to long service life as regular gas turbine maintenance.