Fuel Flexible Power Generation to electrify Africa

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Abstract

In order for industry to grow, economies to expand and living standards to improve, Africa needs a low cost source of power. In Western economies, natural gas is the fuel of choice, providing clean low cost electricity at all scales – from Combined Cycle Power Plant producing thousands of MW to small-scale Cogeneration schemes, some even at kW scale. But this model is not necessarily applicable to Africa, as the power system and gas pipeline infrastructure may not exist, or not be sufficiently reliable, to provide an uninterruptible supply of electricity. In more remote locations, natural gas is not necessarily a suitable fuel due to issues around availability and the cost of constructing a pipeline network, so making better use of locally available or easily transportable low cost fuels is therefore desired. While oilfields can use the produced crude oil as a fuel for power generation, the lower cost refinery products, such as Heavy Fuel Oil (HFO), can be used as the main or back-up fuel for electricity production, freeing up premium fuels like #2 Diesel for transport applications. But using these types of low cost fuels creates additional technical challenges, especially for maintenance of the generator sets in more remote locations to ensure power availability. This paper looks at how gas turbine technology originally designed in the 1950s was developed and has been improved in recent years to meet the requirement to use these high viscosity, low cost liquid fuels to provide local power for industry and communities with minimum maintenance needs, and looks at the application of this technology for a 50 MW power plant to be installed at Edo Cement in Nigeria.

Introduction

Energy can be converted to electrical power and heat from numerous sources and in numerous ways. The ideal energy source and ideal converting technology differ between different geographical areas on earth. In Western economies, natural gas is the fuel of choice, due to the relatively low cost but also because of that the energy conversion can take place with minimum negative environmental effects. Due to radically different conditions in other parts of the World, such as population density, geological and topographical differences as well as distance from natural gas fuel sources to population concentrations, natural gas is not necessarily the first choice in other places in the world. Several such regions can be found on the African continent. While some regions, Northern Africa and parts of Southern and Western Africa have similar
conditions to Europe and the US, regions like Central and Eastern Africa are currently lacking a sufficient and reliable pipeline infrastructure for natural gas. In this case, power producers and industries will be dependent on the supply of liquid fuels or locally available gaseous fuels as the main or back-up fuel, which in turn affects which power generation technology can be best utilised. For many years the ideal solution for power generation on liquid fuel oils has been reciprocating engines due to their capability to run on residual heavy oils, which is the cheapest alternative in a relatively expensive group of fuels. The reciprocating technology offers high electrical efficiency, which is considered by far the most important factor since it affects the single largest part of the operational cost. This advantage has in many cases balanced the disadvantages such as high operation and maintenance cost, high lubrication oil consumption and investment cost. Another disadvantage is the poor emission performance, which has forced the World Bank to have more relaxed emission recommendations for power plants based on reciprocating technology than for example gas turbine plants. Now when natural gas becomes available in a larger part of Africa not only through expansion of pipeline networks, but also through the increased availability of liquefied natural gas (LNG) on the market, again the demands on the power generation technology changes. It is now increasingly important to have technology that can use both gas as well as low premium liquid fuels reliably and with minimum environmental impact. This makes the Siemens 19 MW industrial gas turbine SGT-500 (formerly GT35) an interesting alternative in many African power generation projects.
1. **SGT-500 – a fuel flexible industrial gas turbine**

Introduced to the market in the mid-fifties, the SGT-500 has traditionally been sold for simple-cycle applications wherever reliable operation has been the most important feature of the power generation equipment. Since its introduction, the SGT-500 has built a great track record of fuel flexibility both on liquid and gaseous fuels. The capability to burn a wide range of fuels is due to the main design features chosen when the SGT-500 was developed in the early 1950’s. At that time the available fuel for gas-turbine-based power generation was mainly heavy fuel oil: consequently the SGT-500 was provided with seven roomy combustor cans to maximize the residence time within the combustors as well as burner injectors with a spill flow system for stable atomization and the possibility to control viscosity by heating and recirculating the fuel. Recirculating the fuel, (minimum 10% of the total flow is always returned to the minute tank), also prevents burner tip coking thanks to its cooling effect. The dependable fuel system was actually more or less copied and scaled from that used in those days on conventional steam boilers, and the burners were designed to accept liquid fuels with viscosity up to 25 cSt. With the special heavy fuel system of SGT-500 that has a capability to heat the fuel up to 150 deg. C, it means that the turbine can be operated on all standard bunker oils that are available on the market today.
Both the high-pressure and low-pressure turbines were designed without internal cooling of blades and vanes, simply because manufacturing technologies were not advanced enough at that time to provide the possibility of that technical solution, but that has proved to be an advantage and another key feature for liquid fuel flexibility. The uncomplicated design of the hot gas path has a positive effect in this respect, since the turbine temperature must be kept fairly low (865°C at full load), thus gaining significantly better corrosion resistance compared to a gas turbine with higher turbine inlet temperature. These rugged turbines have no complicated geometries for sealing between stator and rotor, enabling on-line washing of the turbines with solid media complemented with off-line water washing. This is a prerequisite when operating on highly contaminated ash-forming fuels, such as different crude oils and HFO, in order to maintain component lifetime and turbine efficiency during the long operation time between overhauls, and is an advantage not only for high viscosity fuels. The corrosion resistance is also a vital feature for application in oil well power generation when fields with lighter crude oil are explored. Not only offshore but also onshore, the ability to operate directly on the washed and filtered crude oil that is being lifted as well as the associated gas is a compelling feature when selecting power generation equipment.
2. Liquid fuel properties – viscosity and carbon residue

When assessing if a liquid fuel is suitable for injection into the combustion chamber of a gas turbine, the first parameter that should be checked is the viscosity. If the viscosity is higher than the design limit of the injection system and burners when the fuel is heated to the maximum permissible temperature (limited either by system capacity or fuel properties), there is no need to proceed and check other parameters of the fuel. The fuel must have a certain viscosity since the burners where the fuel is injected into the combustion section are designed to give optimized atomization for flame stability, flame position and flame profile. This ensures maximum combustion efficiency, minimum production of nitrogen oxides (NOx) and maximum lifetime of hot gas path components. If the viscosity is above the specified maximum limit (too low a viscosity is generally not a problem for the combustion, but could be an issue due to low lubricity, which causes rapid wear of the liquid fuel pumps), it can be reduced either by heating the fuel, or by blending the fuel with a component that dissolves in the main fuel and has a lower viscosity, but if this method is used, the operator has to ensure that the blend is stable.

The preferred method is normally heating, since blending in most cases results in higher costs than if the fuel is just heated. The first limitation one reaches with regards to heating is 100°C
due to the boil off of water. All liquid fuels contain a small amount of water, which at atmospheric pressure will boil off at 100°C and cause cavitation in the fuel pumps. To extend the heating above 100°C, it is consequently necessary to pressurize the fuel before it reaches the feed pumps in order to avoid cavitation. The upper limit for heating the fuel with a pressurized system is then limited by components such as manifolds and valves. The SGT-500 pressurized Heavy Fuel Oil System has a capability of 150°C, which could be expanded to 165°C through a redesign of the liquid fuel manifold, should that be required. Above 165°C, the fuel temperature is likely to be the limitation due to fuel coking in fuel system and burners.

Most aero-derivative and industrial gas turbines require a fuel viscosity at injection that is lower than 10 cSt and, without means of pressurizing the fuel, this limits the utilization of liquid fuels to the higher quality liquids, such as #2 diesel and kerosene with a maximum viscosity corresponding to distillate fuels.

The SGT-500 burners were originally designed to accept 25 cSt at the injection point. With the current pressurized liquid fuel system, which allows heating up to 150°C, it means that the SGT-500 has a capacity to operate on fuels with viscosity higher than IF1000 (IF380 is the most common standard bunker oil). With a redesign of the fuel manifold and increasing of the temperature limit up to 165°C, it is possible to utilize oils heavier than IF2000 without blending with lighter components.
Another parameter of importance is the Carbon Residue (CR). CR is the percentage of coked material remaining after a sample of fuel oil has been exposed to high temperatures (under ASTM Method D 4530 or similar). This is a measure of the tendency of a fuel to form carbon deposits during combustion and indicates the relative coke forming tendencies of heavy oils. CR is also a measure of the complexity of the hydrocarbon constituents in the fuel. As the CR increases, typically also the asphalthenes content of the heavy oil will increase. Such slow burning, high boiling point constituents gives a high heat radiation when combusted. Hence, CR will be an indirect measure of the flame radiation and heat transferred to parts exposed to the flame. Also, it is a measure of how difficult the fuel is to combust and consequently also how long time it takes to reach complete combustion. The logic here is that the available combustion volume, and thus residence time in the combustor, also determines to what extent “difficult” fuels can be fired in the combustor. A small combustor cannot accept as high CR-values of the fuels as a bigger combustor. The ability to combust all fuel injected is not only dependent on the size of the combustor, but also on the firing temperature - the higher the CR value, the higher the load must be to fully combust all injected fuel and therefore a gas turbine can accept higher CR-values of the fuel on higher loads than it can accept on lower loads. When increasing the load, it is possible to switch to the high CR fuel, which then is used at operation in the normal operation load range. The suitable point of fuel change is depending on the CR value, but for economic reasons it is normally not viable to use a high CR fuel that cannot be used below 50% load. Also, a heavy fuel with high CR-value is more difficult to ignite and therefore it can be necessary to equip the gas turbine with a separate system for start-up.

In a test that was performed in 2006, the influence of viscosity and CR value in the SGT-500 was studied. The viscosity and CR value were controlled by means of switching between fuel qualities and varying the temperature of the fuel. The results were also compared with references on regular diesel oil. Parameters that were of most interest in addition to the standard operation parameters, were emissions (which also show level of complete combustion) and metal temperatures in the combustion section. The test concluded that both viscosity and CR value affects flame profile and flame radiation, and that the parameter that has the biggest impact on
the metal temperatures in the combustion section is the CR value. Both increased CR value and viscosity results in movement of radiation from the back end of the combustion section to the front end. Especially with higher CR value, the temperature in the first third of the combustor cans is increased and the temperature in the last third and gas collector is decreased, see Figures 5 and 6.

Figure 5. Location of thermocouples on the combustor can
Figure 6. Combustor can temperatures

Another test was performed in 2008 where metal temperatures in the combustion section as a result of increased load, i.e. increased turbine inlet temperature, were studied. It could after that be stated that the rear section of the combustor is the part that is most affected by increased firing temperature. A conclusion based on these two different test runs, is that since the temperature is decreasing at the back end of the combustion section when operating on high viscosity- or high CR fuels, the lifetime of the turbine section is not reduced with regards to these parameters. Also the lifetime of the combustion section is not reduced more on high viscosity- or high CR fuels than on regular diesel oil, since there is just a redistribution of the radiant heat from the hottest section to a section with lower temperature. The hottest section will be changed from the back end to the front end, but the maximum temperature will not be higher than for operation on regular diesel oil and consequently the lifetime consumption formula used for regular diesel oil can also be used unaltered for high viscosity- and high CR fuels.

Since the heavy fuel oil test was performed, two units have been in operation in marine propulsion duties on straight run HFO (i.e. low CR value fuel) with the viscosity value of the
fuel at injection set at 16 cSt. The operation profile of these turbines also means that they regularly are operated on peak load and often at levels that stress the turbines 10 times more than at base load. The condition of the turbines has been checked regularly and the only notable deviation compared to other turbines running on lighter liquid fuels (taking also the regular peak load operation into consideration), is that oxidation and buckling of the combustor cans occur to a larger extent. In spring 2012 successful tests were made to shape the flame with the adjustable burner swirl air, which resulted in reduction of critical metal temperatures by up to 50 °C. The turbine components do not show a higher degradation rate than that regarded as normal for operation on regular diesel oil. Despite the challenging operating regime, the availability of these units has always been maintained above 99.5%.

3. Bi-fuelling with the SGT-500

While this paper has concentrated so far on use of crude oil and HFO as a gas turbine fuel, it is also recognized that in some instances there are also small quantities of associated gas produced alongside crude oil in an oil well. When present in sufficient quantities, this gas is commonly used to fuel gas turbines, but one common characteristic of heavy crude oil deposits is a low Gas-Oil Ratio (GOR) which can create the situation where there is insufficient associated gas to provide all the fuel gas required to meet the needs of the power generation plant. So as to avoid flaring or re-injection of small quantities of associated gas, it is possible to use the associated gas as a percentage of the total fuel input required by the gas turbine, with liquid fuel making up the balance.

Also in applications where pipeline natural gas is used as the main fuel, bi-fuelling offers a mitigating effect on operational disturbances and fuel cost increase in case of events that don’t stop the gas supply completely, but only reduce the flow. Liquid fuel can then be used to compensate for the reduced gas supply and operation will be maintained with lowest cost of electricity generation possible.

41 SGT-500’s with dual fuel (gas/liquid) have been delivered since 1978. The majority of these units are only commissioned for switching between gas and liquid fuel during operation and not for continuous operation on liquid and gaseous fuel at the same time. However three units
installed offshore have been commissioned for continuous mixed operation and so far (after more than 10 years of operation), no operational disturbances or deviations from expected maintenance requirements are recorded. It is however not clear to what extent mixed operation has been used in these three units. It is important to note that a dual fuel unit, or one set up for bi-fuelling, is capable of operation on 100% gas fuel or 100% liquid fuel. In gas fuel operation, providing sufficient gas is available, a continuous liquid fuel pilot is not required.

The SGT-500 fuel injectors are equipped with a swirl generator for controlling the atomization of the fuel when it enters the combustion chamber (refer to Figure 2). The swirl air flow can be adjusted manually in order to optimize the combustion in each of the 7 cans. At mixed operation the gas flow will have a similar effect on the liquid fuel atomization as the swirl air and thus the swirl air must be adjusted to a level in between what is valid for 100% liquid fuel and 100% gaseous fuel.

If a unit is commissioned for just switching between liquid and gaseous fuel, and not for continuous mixed operation, gas is used for purging the liquid fuel system to avoid coking of fuel in the piping and liquid channels of the burners when the system is not in operation. At 100% liquid fuel operation the gas system is purged with pressurized air to prevent hot gas from circulating in the gas channels and gas manifold. For mixed fuel operation there is a minimum liquid flow required to obtain sufficient pressure difference between liquid fuel supply pressure and combustor pressure to ensure proper atomization and to prevent hot gases from going backwards into the liquid fuel channels of the burners. The minimum flow is increased with reduced gas chamber pressure, i.e. reduced load. The same principle applies for the gas flow: to avoid that hot gas flowing backwards into the gas channels of the burners, a minimum gas flow is required, which increases as the load is reduced. On full load the minimum ratio is approximately 5% for liquid fuel and 22% for gaseous fuel, which increases to approximately 23 and 52% respectively at 10% load. If it is beneficial from an operation flexibility point of view to reduce the minimum flows even further, it is also possible to run single burners in bi-fuelling mode while the others operate on single gas or liquid only. This makes it possible to reduce the minimum flows to 1/7 of nominal bi-fuelling flow limits.
4. NOx emissions from HFO-generated power

Power generation based on low grade liquid fuels like crude and HFO has the recent years been questioned not only in the Western economies, but also globally due to the fact that modern technologies for reducing emissions of oxides of nitrogen (NOx) cannot be applied for these types of fuels. Natural gas is always the preferred fossil fuel of choice since it creates the lowest CO2 emissions and also is an excellent fuel for the dry low emission combustion systems that all gas turbine manufacturers offer as a standard feature or option on their most recent and high performing gas turbine models. However, sometimes operation on natural gas is simply not an option. It can be for the total period of a power plant’s life or during long or short periods when natural gas is not available, and in many cases the only viable option is then to run the power plant on low grade liquid fuels, which normally incurs a significant increase in environmental pollution. However, with a power plant based on gas turbines with HFO capability that is not the case. Water injection has been used in gas turbines for more than 50 years, initially for power boosting during start-up and later for continuous power boosting, but it was not until the 1980’s that water injection was applied primarily for the purpose of emission reduction. When development of combustion systems targeting reduced NOx emissions took off in the 1970’s, injecting water or steam into the combustion zone was the first reliable technique to reduce the flame temperature and thus achieve a considerable reduction in NOx production. Already at that time, it was possible to achieve NOx levels below 60 ppm @ 15% O2 with maximum fuel/steam or water ratio. On the SGT-500, water and steam injection has been available as an optional feature since the early 1980’s. When operating on HFO on full load, NOx emissions will be reduced from 360 ppm dry to less than 50 ppm with water injection at a water/fuel ratio of 1.1. An additional benefit with water injection is that the power output from a SGT-500 gas turbine or combined cycle plant based on the SGT-500 will increase by approximately 10%.
5. Operation experience and maintenance philosophy

The latest SGT-500 order is three units for a tri-fuel application (Natural Gas/HFO/diesel) in Nigeria. Apart from tests, there have been in total 19 SGT-500 units running on crude oil or HFO, together totaling more than 850,000 operational hours, and the high time unit has passed 90,000 hours of operation. For some of these units that are operating continuously at full load (turbine inlet temp. 850 deg. C), a substantial dosing of chemical inhibitors for high amounts of heavy metals is required, which also increases the requirement for turbine cleaning. As a result of this, a special cleaning system and optimized washing procedure have been developed for off-line washing to remove deposits not only on the compressor but also on the power turbine. It might be a surprise to some, but with correct fuel treatment and carefully performed operational maintenance, including cleaning of the turbine section, the SGT-500 fleet that operates on crude oil and HFO demonstrate availability and reliability almost on the same level as for the fleet that operates on natural gas or high quality liquid fuels. Typical figures for this fleet are 95% availability and 99% reliability. One should also be aware of that these units are operating on full or even peak load, and by reducing the load below 94% of full load, the time between overhaul is doubled due to reduced oxidation and thermal stresses in the hot section, and consequently the
availability figure in such a case would increase to 96%. Further the maintenance philosophy for these units is on-site maintenance and by utilizing an ‘engine swap’ concept, the availability figure would increase by an additional 1%.

Figure 8 describes the maintenance program for HFO operation over an 18 year period if the load is reduced below 94% of full load, indicating the need for only one minor and one major overhaul performed after 6 and 12 years of operation. In this scenario and by using an engine swap philosophy, scheduled downtime is less than 50 days in an 18 year period.

![Figure 8. SGT-500 Maintenance Program for HFO operation below 94% of full load](image)

6. SGT-500 tri-fuel capability compelling feature for Power Generation in new Cement Plant

The latest order for SGT-500 gas turbines is an example where the capability to operate on HFO or regular diesel oil as back-up for natural gas was the compelling feature when EDO Cement decided to buy 3 SGT-500 as the power generation solution for their new cement plant in
Okpella, Nigeria, which will be commissioned during the second half of 2014. The power for the cement plant’s own needs is mainly to be based on natural gas-fuelled power generation, but as pipeline supplied natural gas is unreliable in Africa in general and in Nigeria specifically, availability of one or preferably two back-up fuels is crucial for uninterrupted and profitable cement production. Frequent disturbances on the natural gas supply net must unfortunately be expected and can in the worst case last for several months, which puts high focus on minimising the cost of the back-up fuel. Prices of high premium liquid fuels can often be more than twice the price of residual fuels like HFO, so HFO capability will reduce operational costs considerably during periods when operation on back-up fuel is required. With the tri-fuel capability (NG/HFO/diesel) of the units ordered for the new cement plant, maximum availability of the power plant is ensured at the lowest possible fuel cost.

7. Conclusions

While pipeline quality natural gas will remain the preferred fuel of choice for gas turbine power plant and cogeneration installations, Siemens’ proven experience with the fuel flexible SGT-500 industrial gas turbine shows that there are alternatives available to compensate for brief gas supply interruptions or longer term non-availability of a natural gas supply. Due to the unique design features that were set by the development engineers more than 50 years ago, the SGT-500 fulfills today’s requirements on fuel flexibility and emission performance. With this gas turbine model, non-refined or non-premium fuels like crude oil and HFO can provide low cost alternative fuels to ensure security of energy supplies with emission performance far better than the World Bank’s relaxed recommendations for other more polluting power generation technologies.