Heavy Crude Oil as a Fuel for the SGT-500 Gas Turbine

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Summary

Brazil has Offshore Heavy Oil fields where insufficient associated gas is present to fuel a conventional gas turbine power plant during the whole field life, with only treated heavy crude oil available as the power plant fuel.

The SGT-500 is one of the few gas turbines which have capability to operate on Heavy Fuel Oil, something normally associated with diesel engines. It is proven that the SGT-500 can operate continuously on liquid fuels with viscosity corresponding to IF700 with no requirements for blending with diesel oil.

While heavy crude oil is suitable as a gas turbine fuel, it creates challenges which must be handled through fuel pre-treatment, fuel injection system functionality, and operation and maintenance strategy. This paper discusses the relevant considerations in respect to fuel viscosity, fuel properties such as heavy metals-, alkali metals-, sediment contamination and carbon residue, and how they can be reliably handled. Operational aspects such as the start-up process, impact on component life and maintenance intervals are also discussed.

The paper also examines the possibility of bi-fuelling – operating simultaneously on crude oil and gas – and provides feedback on the operational experience gained on the SGT-500 units operating on light crude oil and Heavy Fuel Oil.
1. 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 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 desired 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 contains a small amount of water, which at atmospheric pressure will boil off at 100°C and cause cavitations in the fuel pumps. To extend the heating above 100°C, it is consequently necessary to pressurize the fuel before it reaches the feeding pumps in order to avoid cavitations. 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 is currently limited to 150°C due to the fuel manifold. If required, a redesign of the manifold would easily increase the limitation to 200°C. However, the fuel temperature is likely to be limited before that 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 20 cSt at injection. 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 IF700 (IF380 is the most common standard bunker oil). With a redesign of the fuel manifold and increasing of the temperature limit up to 200°C, it would in theory be possible to utilize oils heavier than IF1000 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 correspondingly). 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 asphaltene 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 can not 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 and therefore a gas turbine can accept higher CR-values of the fuel on higher loads than it can accept on lower loads. Also, a heavy fuel with high CR-value is difficult to ignite and therefore it is in most cases necessary to equip the gas turbine with a separate system for start up and low load operation. When the load is increasing, it will at a certain point be possible to switch to the high CR fuel, which then is used at operation on higher loads. The definition of higher loads is depending on the CR value, but for economic reasons it is normally not viable to use a high CR fuel that can not be used below 50% load. The higher the CR value, the higher the load must be to fully combust all injected fuel. In a test that was performed in 2006, the influence of viscosity and CR value was studied. The viscosity and CR value were controlled by means of switching between fuel qualities and heating the fuel less or more. 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 1 and 2.

Figure 1. Location of thermocouples on the combustor can
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. 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- and reliability figures have always been maintained above 99.5% (availability and reliability becomes the same, since all planned maintenance can be performed outside scheduled operation).

2. Fuel treatment of crude oil

Crude oils must be treated in order to meet gas turbine requirements on limits of metals and other contaminants in fuels. Because of the large variability in composition among these fuel types, it is necessary to undertake a case by case examination of the fuel treatment process for all specific fuels. As mentioned earlier, heavy fuels must normally be heated to reduce the viscosity.

Crude oils often contain high amounts of alkali metals (Na, K) and heavy metals (V, Ni, etc). Introduction of these in the engine will result in accelerated deposit formation and high temperature corrosion in gas turbine hot sections. The major corrosive constituents formed during combustion of crude oils are vanadium pentoxide ($V_2O_5$), sodium sulfate ($Na_2SO_4$), and other aggressive low melting forms in the $Na_2SO_4-V_2O_5$ and $Na_2O-V_2O_5$ systems. The lowest melting points can be almost as low as 500°C. An internally developed method is used to determine the sticking temperature of the ash. This temperature must be above 900°C if sticking to the turbine blades should be avoided.

Alkali metals are generally water soluble and are found in the water phase of the fuel. Water washing and centrifuging must be used to reduce alkali and other water soluble metals in the crude oil. A limiting factor for good efficiency of the centrifugal separators is high fuel density. Fuel heating prior to separation assists in the process since the fuel density changes more rapidly with temperature than the water density. However, the presence of volatile components in the crude oil might provide an upper limit for heating.

Vanadium is a naturally occurring component of the oil and is oil soluble. Consequently, it cannot be removed by means of washing and separation. Its corrosive effect must instead be taken care of by the use of chemical inhibitors. The most important element in these additives is magnesium, which reacts with vanadium to form compounds that melt at high temperatures, thus inhibiting the effect of vanadium pentoxide which has a low melting point. An optimum dosage ratio will result in the formation of magnesium orthovanadate ($3MgO\cdot V_2O_5$) that has a melting point above 1200°C. The deposition rate in the turbine will increase due to the additive treatment and therefore regular washing of turbine online and offline will be necessary for application with high ash contents in order to minimize losses in power output and efficiency. Local regulations set by authorities may limit maximum permissible ash or particle content and this might also limit the total amount of ash in the fuel entering the engine.

Water and sediment can be separated from the fuel by filtration and centrifuging. Free water in the fuel can lead to corrosion and fuel degradation, and the presence of water provides a starting
point for microbe growth in fuel tanks, etc. These microbes live in the water phase and feed on the oil in the fuel-water interface. The resulting slime, sometimes corrosive, will cause fouling of fuel filters, valves and nozzles. Sediment is a contaminant found in different quantities in liquid fuels often depending on storage and transport conditions. The sediment can be organic (sludge, asphaltenes deposits, etc) and inorganic (rust, sand, dirt, etc) and may result in plugging and abrasive wear of both fuel system and engine components. Apart from the use of filters and separators it is very important to employ proper fuel handling procedures during storage and filling. After filling, storage tanks must be settled and drained before use. Regular draining the tank bottom for water will also minimize the risk for bacterial growth.

Crude oils often contain volatile components which results in low flash point. Explosion proof equipment is often required. Specially designed fuel systems might also be needed depending on the volatility and vapor pressure of the crude oil in order to reduce the risk for cavitations.

3. SGT-500 fuel flexibility

The SGT-500 has a great track record of fuel flexibility both on liquid and gaseous fuels. In practice, even heavy fuels can be burnt smokeless and light crude oil can be burnt below visibility limit over the entire load range. The reason for the capability to burn a wide range of fuels is the main design features that were chosen when the SGT-500 was originally developed in the early fifties. To tolerate the heavy oil available for power generation in those days, it was provided with 7 roomy combustor cans, giving very low thermal stresses and long residence time for combustion. Refer to Figure 3.
The SGT-500 was also equipped with burner injectors with spill flow system for stable atomization and possibility to control viscosity by heating and recirculating the fuel. Refer to Figure 4. The recirculation of fuel, which at all time during operation is minimum 10%, also minimizes the risk of burner tip coking thanks to the cooling effect that this feature gives. The fuel system was copied and scaled from the conventional steam boiler technology of the time and the burners were designed for accepting liquid fuels with viscosity up to 20 cSt (the HFO test in 2006 indicated that the capability is even higher than that).

Both the high pressure- and low pressure turbine were designed without internal cooling of blades and vanes, which has proved to be a key advantage for fuel flexibility. The uncomplicated design of the hot gas path has a positive effect in this aspect, since the firing temperature must be kept fairly low and this leads to better corrosion resistance compared to a gas turbine with higher turbine inlet temperature. The firing temperature on a multi-shaft gas turbine like the SGT-500 is also substantially reduced on part loads, giving additional margin to corrosion phenomena, while
the hot gas path components are made from high chromium materials, which improve the corrosion resistance still further. The rugged turbine designs also don’t have any complicated geometries for sealing between stator and rotor and that enables on-line washing of the turbines with solid media complemented with off line water washing, which is a prerequisite to maintain component lifetime and turbine efficiency during the long operation time between overhauls, when operating on highly contaminated fuels. Refer to Figure 5.

![Cross section of SGT-500 high- and low pressure turbine](image)

**Figure 5.** Cross section of SGT-500 high- and low pressure turbine (arrows illustrating cooling- and sealing air flow)

### 4. Experience on crude oil

Apart from tests, there have been in total 11 SGT-500 units running on crude oil totalling together more than 450 000 operation hours, and the high time unit has passed 75 000 hours of operation. Today’s experience of crude oil operation is based on lighter crude oils. One example is crude oil with a viscosity at 6.4 cSt@40°C and an API gravity at around 32. Another example is crude with a viscosity at 2.2 cSt@40°C and an API gravity at around 43. For these units, that are operating on full load (turbine inlet temp. 850 deg. C), a substantial dosing of chemical inhibitors is required, which also increases the requirement for turbine cleaning. As a result of this, a special cleaning equipment and optimized washing procedure have been developed to off line remove deposits also in the power turbine. This off line cleaning can be synchronized with the off line washing of the compressors.

It might be a surprise to some, but with correct fuel treatment and carefully performed operation maintenance, including cleaning of the turbine section, the SGT-500 fleet that operates on crude oil can present figures for 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 the fleet operating on
crude oil are 94% availability and 98% reliability. One should also be aware of that these units are operating on full load, and by reducing the load to 90% 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 a swap engine concept the availability figure would increase additionally by 1%.

Figure 6 describes the maintenance program for crude oil operation over an 18 years period if the load is reduced to 90% of full load, including 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 6.** SGT-500 Maintenance Program for crude oil operation at 90% of full load

5. Bi-fuelling with the SGT-500

While this paper has concentrated so far on use of crude oil as a gas turbine fuel, it is also recognized that in some instances there is also small quantities of associated gas produced alongside the crude oil. 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. 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.

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 3. 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. At mixed operation there is a minimum liquid flow required to obtain sufficient pressure difference between liquid fuel supply pressure and combustor pressure 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.

6. Conclusions

The simple design of the SGT-500 allows a wide range of both gas and liquid fuels to be considered. Operation on light crude oil and Heavy Fuel Oil has been proven, and tests demonstrate the potential to burn suitably treated heavier crude oils too. This wide fuel capability enables the SGT-500 to be considered for use on Offshore heavy oil developments, where the compact package size, low weight, high availability and long maintenance intervals maximize the production uptimes and minimize space requirements and the number of operator interventions required.