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SUITABILITY OF LIQUID BIOFUELS IN SOLAR®TURBINES INCORPORATED DLE INDUSTRIAL GAS TURBINES

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ABSTRACT

To meet the goals of 2015 Paris Climate Agreement, there is an effort to decarbonize energy across the globe for which all the renewable energy sources are getting evaluated. For many power generation applications there is a growing interest in using biofuels to replace fossils-based fuels, such as diesel and natural gas. Because of being plant-based, liquid biofuels, such as biodiesel and ethanol, have the potential to provide carbon-neutral power over its lifecycle basis. Many distributed power generation sites, such as universities, are interested in the feasibility of burning these biofuels, in stationary gas turbines to reduce their carbon-footprint as well as earn tax credits. Solar Turbines is at the forefront of providing fuel-flexible solutions to its distributed power generation customers. It has qualified several of its gas turbine models using both the conventional and dry low emissions (DLE) combustion systems on various biodiesel blends. In this paper the results from the combustion rig tests with DLE combustion injectors using B20 and B50 biodiesel blends and their comparison with those of No. 2 diesel and natural gas fuels are presented. The results are summarized in terms of gas turbines emissions and durability. The emissions (NOx, CO, UHC) from biodiesel blends were similar to, or less than that of Ultra Low Sulfur Diesel (ULSD), but higher than natural gas. Impacts of fuel properties on storage, handling and gas turbines operations are discussed. Finally, future development opportunities are presented.

INTRODUCTION

The biodiesel fuels are sold in the market as BXX blends, for example B5, B20, B100 etc., which consist of XX% vol. of biodiesel blended with No. 2 diesel fuel, such as ULSD. The combustion of B100 (100% biodiesel) fuel results in about 80% reduction in carbon dioxide emissions on a life-cycle basis compared with that of ULSD, which could increase to 100%, if zero-carbon energy is used in its supply chain [1, 2]. It has led to increased interest from policy makers in exploring biofuels to help with decarbonization of electrical grids.

The National Biodiesel Board (NBB) is at the forefront of biodiesel research and testing, as well as facilitating quality control of the production processes and supply of high-quality biodiesel fuels through the development of stringent ASTM fuel standards and implementation of the BQ-9000 fuel quality program in the USA. One of NBB's initiatives is to explore the suitability of biodiesel fuels in power generation applications with respect to technology readiness. NBB has identified the Northeast States of the US to be at the forefront of public policy to reduce carbon dioxide emissions, and it sees the region as a potential opportunity to explore the use of B20 or B50 fuels. Currently, B20 fuel is available in Massachusetts for residential heating. Also, B20 is used by Harvard University in their transportation fleet [3]. Per the state's environmental policy initiatives, the biodiesel content in the fuel is expected to increase to B50 by 2030 [4].

Solar Turbines partnered with NBB to perform combustion rig tests to prove the suitability of B20 (20% vol. biodiesel blended with 80% vol. ULSD) and B50 (50% vol. biodiesel blended with 50% vol. ULSD) in gas turbines as a drop-in fuel for ULSD. Solar Turbines has many of its generator package models installed at universities across the USA. It is having discussions with some university partners in the Northeast to perform field tests to demonstrate biodiesel capability.

The paper presents the results of single-injector combustion rig tests using B20 and B50 with Solar's Titan™ 250, Titan™ 130, and Taurus™ 70 SoLoNOx™ fuel injectors at simulated engine conditions. The emissions (NOx, CO, UHC and smoke) and carbon deposition propensity were measured and compared against those of the diesel and natural gas. Although the emissions data measured in the rig tests only correlate within a few ppm of emissions measured in the engine, emission trends correlate very well, so that emissions trends in the rig taken with biodiesel fuels compared to ULSD with engine results will be quite accurate.

PROPERTIES OF BIODIESEL BLENDS AND RISKS

Prior to rig tests, B20 and B50 fuels were characterized based on the fuel samples test data. The key liquid-fuel interchangeability risks were evaluated by comparing their properties with those of ULSD.

The BQ-9000 certified B20 and B50 fuels for the rig tests were provided by Renewable Energy Group (REG) and samples of these fuels were tested at the Inspectorate's fuel analysis laboratory in Houston. The physical & chemical properties and contaminants (solids, free water, trace metals etc.) of the test fuels were measured using the corresponding ASTM test methods. The results (not shown here) were compared with their limits in Solar's fuel specification document (ES 9-98) [5], which are based on Solar's extensive experience with other alternative fuels to ULSD.

The specific gravity, kinematic viscosity, and distillation temperature of B20 and B50 blends were similar to that of ULSD fuel. Hence, atomization, vaporization, and fuel-air mixing of these biodiesel blends, and hence, the NOx emissions were expected to be similar to that of ULSD and were measured during the rig tests.

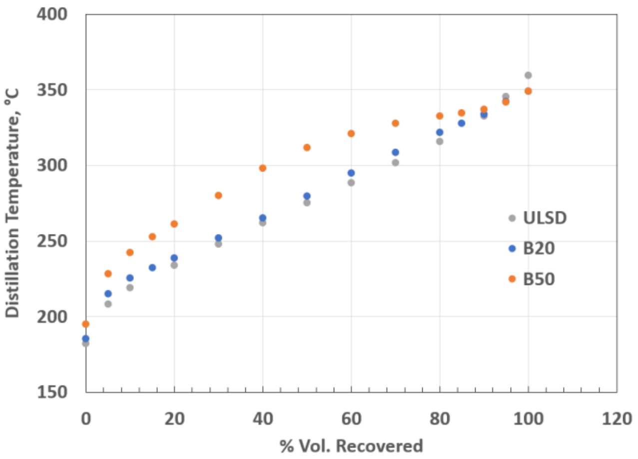

Figure 1. Distillation temperature curves of ULSD, B20 and B50 fuels using ASTM D86

The distillation temperature curves of B20 and B50 were compared with that of ULSD, as shown in figure 1. The distillation temperature curve of B20 is similar to that of ULSD. Therefore, the engine startup risk using B20 is expected to be negligible. The maximum temperature difference between the distillation curve of B50 and ULSD was about 50°F, which indicates that the risk is still low. But if there is difficulty in startup using B50 in the engine, it can be mitigated using a propane torch.

Since B100 fuel has about 10%-15% lower energy content (LHV) than that of ULSD [6], the LHV of B20 and B50 were 0.6% and 3.5% less than that of ULSD, respectively. The impact of lower LHV was compensated by operating the rig at a correspondingly higher fuel mass flow rate.

Combustion stability is characterized by the presence or lack of significant levels of combustor pressure oscillations, or combustor rumble. Extensive analysis, and often engine qualification, is required to verify that different fuel compositions do not significantly change the combustion stability characteristics. Since the physical and chemical properties of the test fuels are close to those of ULSD, the risk was deemed negligible.

None of the other physical and chemical properties and contaminants exceeded ES 9-98 limits, hence, were not concerning.

The biodiesel related properties in these blends due to the B100 portion of the fuel such as, FAME (Fatty Acid Methyl Esters) content, oxidation stability, acid number, iodine number, methanol content, concentrations of mono-, di-, tri- glycerides and total and free glycerin, and cold soak filterability are listed in Table 1, along with the corresponding test methods. These properties are compared with their limits in ASTM D6571 and EN 14214 B100 specs and ASTM D7467 B20 spec. There currently is no spec for B50 fuel.

Table 1. Biodiesel related properties of the B20 and B50 samples

Properties	**B100 ASTM/EN Specs**	**Units**	**Test**	**B20**	**B50**
Fatty acid methyl ester (FAME)		%vol.	EN 14078	19.9	50.2
Biodiesel content		% vol.	D7371	20.6	50.1
Oxidation stability	**3 hr. (B100), min.**	h	EN 15751	8.3	18
Acid number	**0.5 mg KOH/g, max.**	mg KOH/g	D664	0.05	0.09
Iodine number	**120 g/100g, max.**	g iodine/100	EN 14111	3	3
Methanol content	**0.2% mass**	% wt.	EN14110	0.01	0.01
Monoglyceride content	**0.4% mass**	% wt.	D6584	0.036	0.12
Diglyceride content	**0.2% mass**	% wt.	D6584	0.092	0.092
Triglyceride content	**0.2% mass**	% wt.	D6584	0.00092	0.00092
Total glycerine	**0.24% mass**	% wt.	D6584	0.009	
Cold Soak Filterability	**360 s**	sec	D7501	57	64

The injector coking risk due to the presence of Fatty Acid Methyl Esters in the fuel were evaluated during the rig tests.

Biodiesel blends are known to be prone to fuel degradation and microbial growth, which reduce their shelf life. Also, oxidation of fuel can cause fuel system deposits and filter clogging. Oxidation Stability is a measure of fuel storability. From Table 1, the oxidation stability measurements of both the B20 and B50 fuels were significantly higher than the limits in the fuel spec, which indicates that the fuel has longer shelf life and lower oxidation risk. Usually, by following the fuel producers' guidelines and use of appropriate biocides, the shelf life of the fuel will be adequate for most applications.

The higher number of unsaturated carbon bonds present in B100 pose increased risk of the formation of insoluble solids that can clog the injector and filters. The higher concentration of fatty acids in B100 could result in fuel system deposits and increase the likelihood of corrosion. The iodine number and acid number are used to assess these risks. The iodine number and acid number of the fuels were measured and found to be low enough, such that the corresponding B100 values are lower compared with those in ASTM and EN B100 fuel spec. Hence, the risks associated with unsaturated carbon bonds and fatty acids were low.

The contaminants of methanol, glycerin and mono-, di- and tri-glycerides; get introduced in the biodiesel blends, if the bio-crude is not cleaned properly during the manufacturing process. Methanol could impact the flashpoint. High amount of free glycerin can cause deposits in injector, fuel system and storage tank and clogging in fuel system. High amounts of glycerides may adversely affect the cold weather behaviour of the fuel and can cause injector deposits and filter plugging. The methanol, glycerin and glycerides values reported in Table 1are low enough, such that the corresponding B100 values are lower compared with those in ASTM and EN B100 fuel spec, and hence, reduce the associated risks.

Cold Soak Filtration is a performance-based filtration test that is an indicator of the filter clogging tendency of B100 biodiesel in cold weather, due to the presence of contaminants. The reported value in Table 1 is low enough, such that the corresponding B100 values are lower compared with those in ASTM B100 fuel spec, which indicates that the filter clogging tendency of the test fuels is low.

Biodiesel and its blends are known for incompatibility with metals and elastomers. The metals such as, copper, brass, bronze, lead, tin, and zinc, are avoided in the gas turbine fuel systems and combustion systems. Biodiesel may soften or degrade some types of elastomers used in seals and hoses (eg. Nitrile) causing a leak risk. This risk can be mitigated by replacing elastomeric seals and hoses with Viton, which is a material compatible with biodiesel blends. The incompatible materials must be avoided in the fuel storage and delivery system too.

In the rig tests, the impact of biodiesel blends on emissions and injector coking propensity were determined. Fuel quality, storage, and handling risks must be mitigated by sourcing high quality biodiesel blends and following the industry best practices.

DESCRIPTION OF PRODUCTS AND TEST RIG

In this section, short descriptions of the products tested in this study and of the test rig are provided.

Solar uses two combustion system technologies in its gas turbines, namely conventional combustion system that uses diffusion flame combustion and Solar's DLE system, trademarked SoLoNOx that uses lean premixed combustion. Cross-sections of the conventional and SoLoNOx combustion systems are included in figure 2. For a detailed description of the SoLoNOx combustion system and a comparison with the conventional combustion systems, please refer to reference [7].

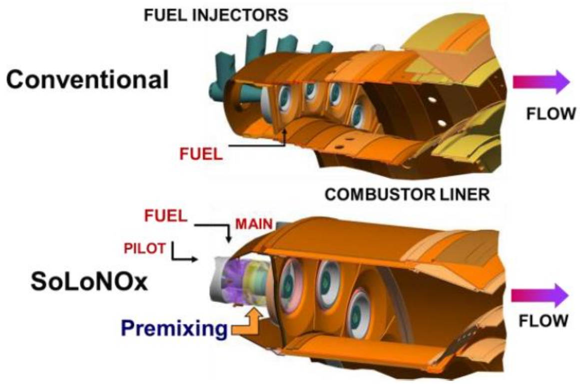

Figure 2. Comparison of Conventional and DLE (SoLoNOx) Combustion Systems

SoLoNOx combustion systems of Titan 250, Titan 130 and Taurus 70 products were the focus of this study. The output power ratings of Titan 250, Titan 130 and Taurus 70 are 23.1 MW, 16.5 MW and 8.2 MW, respectively.

Titan 250 uses a radial-flow fuel injector, while Titan 130 and Taurus 70 use axial-flow fuel injectors.

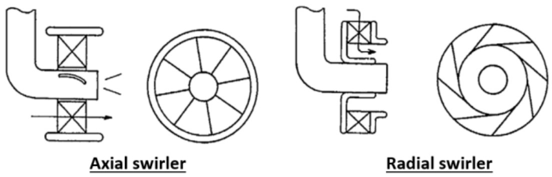
Axial swirler
Radial swirler

Figure 3: Schematics of axial and radial swirlers [8]

The advantage of the radial-flow design is its faster mixing characteristic and short residence time compared with that of the axial-flow design. This reduces the risk of carbon deposit formation in Titan 250 injector. Actual injector designs are Solar's proprietary information, and hence, cannot be shared here. Schematics of axial and radial swirlers are shown in Figure 3 for illustration.

Both the radial and axial fuel injector designs have been developed to prevent deposits from forming with conventional hydrocarbon liquids such as ULSD or kerosene. From a fuel chemistry perspective carbon deposition formation occurs primarily through the peroxide chemistry route, which requires dissolved oxygen [9]. Studies with conventional liquid fuels have shown that this mechanism is dominant in the temperature range of 204ºC to 427ºC [10, 11]. The operating temperatures and pressures of the combustion system for the Titan 250, Titan 130, and Taurus 70 are shown in Table 2.

Based on the previous studies on liquid hydrocarbon fuels the risk of carbon deposit formation in these fuel injector models is very low to low. However, both the Titan 130 and Taurus 70 are just above the upper range of inlet temperature for this mechanism to occur. With the different levels of dissolved oxygen in DLE combustion systems and fuel bound oxygen in biodiesel, a key goal of this study was to prove that carbon deposit formation was still negligible for these engine models.

Table 2. Engine operating temperature

	Compressor Discharge Pressure (atm)	Compressor Discharge Temperature (°C)
Titan 250	22	474
Titan 130	16	432
Taurus 70	15	431

Solar Turbines utilized a high-pressure single can test rig to conduct the combustion experiments. A partial side view of the test rig is shown in figure 4 (a) and a cross section model of the rig is shown in figure 4 (b). The High-Pressure Single Injector [HPSI] combustion test rig is built with a can combustor liner housed in a cylindrical pressure casing. A single fuel injector completes the basic build configuration. The rig is capable of pressures up to 15 atm and preheated air temperatures up to 520°C.

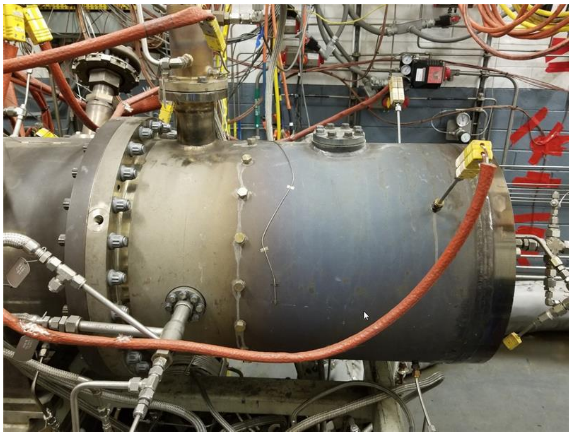

Figure 4 (a). The single injector rig installation located at Solar Turbines combustion test facility.

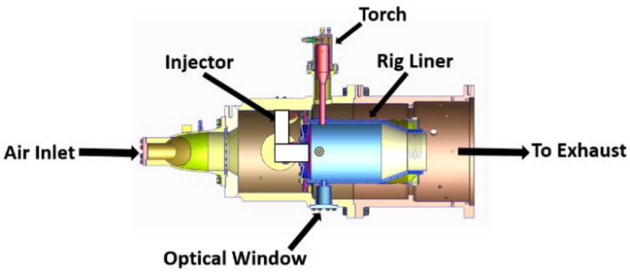

Figure 4 (b). The cross section of the single injector rig

Fuel is supplied to the rig via one of several liquid fuel tanks, where one tank is designated specifically for biodiesel. Hot air, simulating the air compressed from an engine compressor is introduced into the plenum housing the fuel injector. The combustor can liner is cooled with a separate flow of compressed air. This allows precise control of the flow, pressure and temperature of the air fed to the fuel injector. Combustion is initiated using a flame torch located at the top of the casing that passes though the wall of the combustion liner. The torch is ignited using a high-tension spark plug driven by an induction coil. High temperature combustion gases are exhausted to a stack to the center of the image. Combustion exhaust gases are sampled using water-cooled probes and their composition analyzed using standard gas analysis equipment. Emissions were measured in accordance with EPA sampling methods using commercial chemiluminescence NOx analyzer and infra-red CO analyzer. Smoke data was collected using a Bacharach TRUE-SPOT® Smoke Tester (0021-7012) instrument following the procedure outlined in its user’s manual. The sample is taken from a slip stream of the rig exhaust for accessibility.

The rig is instrumented with static and dynamic pressure transducers, flowmeters, and thermocouples to measure critical combustion parameters. Direct flame monitoring in the primary zone is achieved using a camera attached to a housing on the casing. The fuel injector itself may also be instrumented with thermocouples to monitor metal temperatures and to detect flashback. A fuel injector, the associated fuel feed tubes and embedded thermocouples are seen in figure 4 (a).

RIG TEST RESULTS

The single injector rig tests were performed to measure the impact of B20 and B50 fuels on the emissions (NOx, CO, UHC and smoke) and injector coking of Titan 250, Titan 130 and Taurus 70 fuel injectors at the simulated full load and part load conditions. Previously measured rig test data using ULSD and natural gas data at the similar corresponding load conditions with these fuel injectors were used to contrast these results.

Titan 130 and Titan 250 Test Results

First the impacts of B20 and B50 on the performance of axial flow and radial flow injectors designs were studied by testing Titan 130 and Titan 250 combustion systems.

Figure 5 shows NOx emissions data using B20, B50 fuels with Titan 130 and Titan 250 injectors at the simulated full load and part load conditions relative to the corresponding ULSD NOx emissions data. The part load condition for Titan 130 was 60% of rated baseload and that for Titan 250 was 40% load. The NOx emission for natural gas for the corresponding fuel injector and at similar operating conditions were also plotted.

As seen in Figure 5 with increasing biodiesel content in the fuel, reductions in NOx emissions were observed with both Titan 130 and Titan 250 injectors. The Titan 250 injector performed with a smaller relative reduction in NOx than the Titan 130 injector, especially at part load. However, the reduction in part load NOx emissions for the T250 injector is within the measurement uncertainty.

Based on the rig test results, NOx emissions using B20 and B50 fuels will be higher than that of natural gas and are expected to be similar, or lower than that of ULSD in the engine.

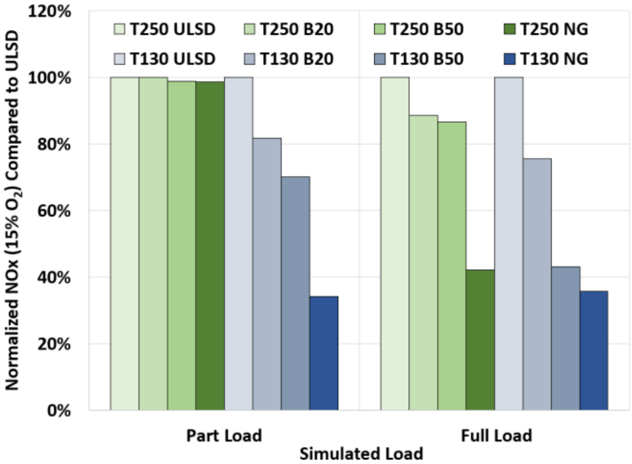

Figure 5. Normalized NOx emissions using B20, B50 and ULSD fuels with Titan 130 and Titan 250 injectors at full load and part load conditions.

There was a slight increase in carbon monoxide and unburned hydrocarbons emissions using B20 and B50 fuels compared to ULSD at the corresponding conditions, as shown in Figures 6 and 7. However, the increases were < 2 ppm of ULSD.

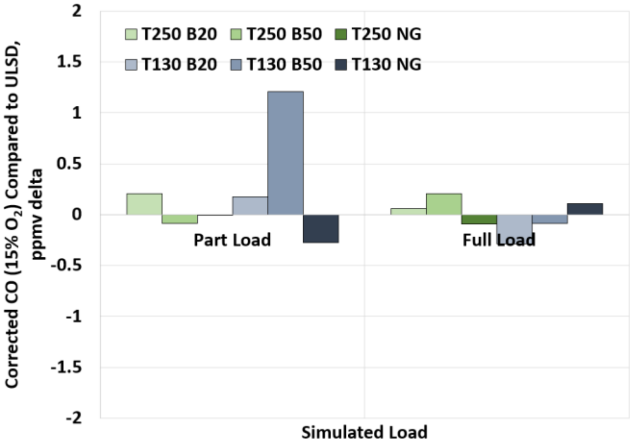

Figure 6. Normalized CO emissions using B20, B50 and ULSD fuels with Titan 130 and Titan 250 injectors at full load and part load conditions.

Smoke emission was also monitored for B20 and B50 fuels and was found to be comparable to that of ULSD. No smoke is seen at full load and part load conditions. At idle condition smoke of around 2 was observed on the Bacharach smoke scale of 0 to 9, using the test method ASTM D2156–09. In general, smoke level below #2 Bacharach is targeted for most gas turbine applications.

A four-hour endurance test is used to assess the injector coking risk from different liquid fuels. Figure 8 shows images of a Titan 130 injector after four hours endurance tests using B20 and B50 fuel at full load and part load conditions compared with a similar 4-hours endurance test with ULSD.

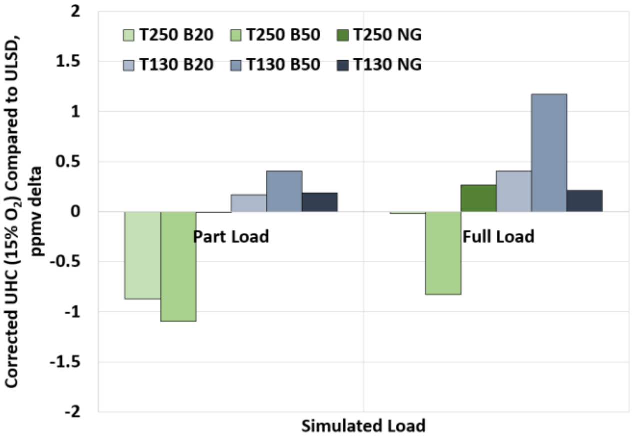

Figure 7. Normalized UHC emissions using B20, B50 and ULSD fuels with Titan 130 and Titan 250 injectors at full load and part load conditions.

At full load conditions minimal carbon deposits were observed with B20. At the part load condition, some minor deposits were formed at the centerbody of the injector, where liquid fuel droplets came into contact with the surface. The carbon deposition level of B50 was found to be slightly less than with B20. The reduced carbon observed when operating on B50 is attributed to the increased biodiesel content in B50 compared to B20, which increases the solvency of the fuel and erodes deposits as they are formed [2].

Figure 8. Minimal carbon deposits inside the Titan 130 injector after four hours endurance tests using B20 and B50 fuels at full load and part load conditions compared to ULSD at part load condition

The images of Titan 250 injector after the four hours endurance tests using B20 and B50 fuel at full load and part load conditions are shown in Figure 9. The Titan 250 radial injector did not experience any carbon deposition over the course of the four-hour endurance test at either full load or part load conditions. The radial flow injector design has an advantage in that it minimizes liquid metal wetting, so the liquid fuel droplets did not have opportunity to leave a carbon deposit from surface vaporization on the inner surfaces of the injector.

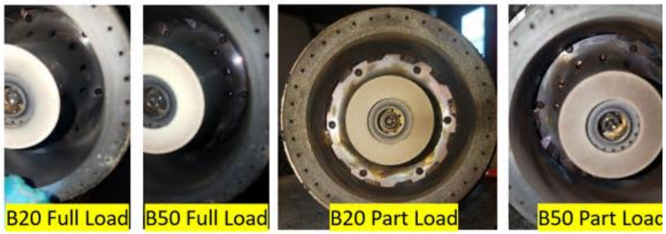

Figure 9. Negligible carbon deposits inside the Titan 250 injector after four hours endurance tests using B20 and B50 fuels at full load and part load conditions

Taurus 70 Test Results

Per Table 2, Taurus 70 operates at the compressor discharge temperature similar to that of Titan 130, but at a lower compressor discharge pressure. To capture the effects of biodiesel blend on the combustion performance using the axial flow injector design at a lower compressor discharge pressure, Taurus 70 injector was tested with B50 fuel only. Figure 10 shows NOx emissions data from the rig tests at simulated full load and part load conditions for Taurus 70 tests, where part load condition was 65% load. The NOx emissions with Taurus 70 using B50 were nearly half compared with that of ULSD.

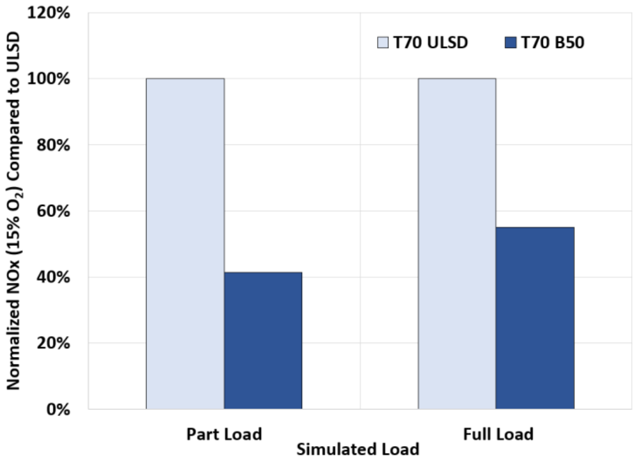

Figure 10. Normalized NOx emissions using B50 and ULSD fuels with Taurus 70 injector at full load and part load conditions.

Figure 11 shows the Taurus 70 CO emissions data at the full load and part load conditions using B50 fuel. The emission levels of both CO at full load are very low and comparable between B50 and ULSD. However, there was an increase in carbon monoxide emissions while operating on B50 at part load. Further investigation of the CO data showed that the higher value was due to operating at a lower flame temperature than planned on B50 compared to ULSD.

The unburned hydrocarbon emissions (not shown) with Taurus 70 using B50 fuel were quite low and comparable with those using ULSD at both the full load and part load.

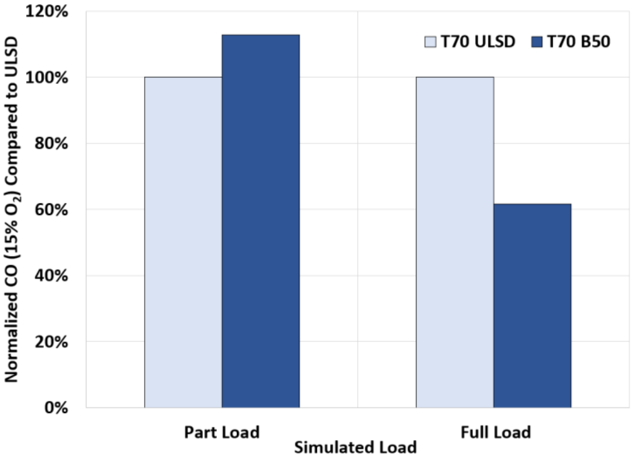

Figure 11 Normalized CO emissions using B50 and ULSD fuels with Taurus 70 injector at full load and part load conditions.

Similarly, the smoke emission (not shown) monitored using the Bacharach scale was also found to be negligible using B50 fuel with Taurus 70.

The images of Taurus 70 injector after the four hours endurance tests using B50 fuel at full load and part load conditions are shown in figure 12. The Taurus 70 injector did not experience any carbon deposition over the course of the four hours endurance tests at the full load and part load conditions.

Figure 12 Negligible carbon deposits inside the Taurus 70 injector after four hours endurance tests using B50 fuel at full load and part load conditions.

CONCLUSIONS AND FUTURE WORK

Single injector rig tests were performed using B20 and B50 fuels with Solar Turbines Titan 250, Titan 130 and Taurus 70 SoLoNOx fuel injectors to assess the impact of these fuels on emissions and injector coking. The properties of the BQ-9000 certified B20 and B50 test fuels were found to be within the ES 9-98 limits and were similar to that of ULSD. This greatly reduced the risks associated with fuel interchangeability. Also, the properties specific to the biodiesel portion of the fuel were found to comply with the ASTM and EN biodiesel specs, further reducing these risks. The results of single injector rig tests using the axial flow and radial flow fuel injector designs of the Titan 130 and Titan 250, respectively, indicated that the NOx, CO, UHC and smoke emissions were similar or lower to that while operating on ULSD. In addition, minimal carbon deposits were observed after four-hour endurance tests. The rig tests with Taurus 70 axial flow injector design, which operates at lower compressor discharge pressure than the Titan 130, showed no adverse impact of B50 fuel on emissions and durability of the Taurus 70 injector. Taurus 70 injector was not tested using B20 fuel. Hence, B20 and B50 fuels were found to be suitable for Titan 250 and Titan 130, and B50 fuel for Taurus 70 SoLoNOx products. B20 is acceptable in Taurus 70 for an engine field test due to the similar performance observed in Titan 130 and Titan 250 tests.

The next step to the successful completion of this study is to perform engine tests on the Solar gas turbine packages operating on B20 and B50 in the field. These tests will be valuable to validate the rig emissions (NOx, CO and UHC) measurement and the thermo-acoustic oscillation characteristics with B20 and B50 fuels. As a further step, B100 fuel will be qualified on Solar products via the rig and engine tests, to take full advantage of the decarbonization potential of biodiesel fuels.

ACKNOWLEDGEMENTS

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