

Performance and Durability of a Generator Set CI Engine using Synthetic and Petroleum Based Fuels for Military Applications

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Abstract

The long term performance and durability evaluation of a compression ignition (CI) engine for a diesel power generator using ultra low sulfur diesel (ULSD) and Synthetic Paraffinic Kerosene, or “SPK”, (S-8) fuels have been investigated under military specifications. The brake specific fuel consumptions (BSFC) were 0.308 ± 0.013 and 0.267 ± 0.019 kg/kW-hr for ULSD and S-8, respectively. The corresponding brake thermal efficiencies (BTE) were 0.287 ± 0.002 and 0.326 ± 0.006 . Degradation of engine performance or engine part wear was not observed during these test periods. Analysis of lubricating oil suggests negligible engine part wear. The frequency and power output of the generator, however, were not as stable with S-8 as they were with ULSD. These power and frequency instabilities can be attributed to higher volatility and lower density and viscosity of S-8, all of which affect the fuel injection characteristics.

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1. Introduction

The higher efficiency, durability, and improved fuel economy [1-2] of compression ignition engines make them very attractive for use in U.S. military equipment in the battlefield from generators to aircraft carriers. Also, the U.S. military has implemented the Single Fuel Forward (SFF or single fuel in the battlefield) Policy [3, 4]. This means that all equipment in the battlefield from generators to heavy trucks and aircraft must be capable of using the same fuel. The Single Fuel Forward Policy requires the use of jet fuel, namely JP-8, JP-5, or Jet A-1. This policy does allow the use of commercially available diesel fuel in the battlefield as an alternate, but only when approved by the Combatant Commander and only when supplying jet fuel is not practicable or cost effective. The U.S. Military, along with the commercial aviation industry, has embraced an initiative that provides that U.S. energy security can be enhanced through domestic production and use of alternative jet fuel produced from various domestic resources such as coal and biomass. Investigation of various fuels such as ultra low sulfur diesel (ULSD) [5-6], synthetic fuels [7-8], JP-8/JP-5 [9-13], and blends of biodiesel [14-15] in military applications is necessary to identify the required operational performance and potential issues. The problematic long-term supplies of oil and increasing knowledge of health effects of JP-8 [17], however, have recently encouraged the U.S. military to foster development of cleaner fuels such as Synthetic Paraffinic Kerosene (SPK); one such SPK is known as S-8, originally proposed as an alternative to JP-8. S-8 is derived from synthetic gas through the Fischer-Tropsch (F-T) synthetic fuel process [16]. Evaluations of F-T fuels, such as SPK (S-8), in military ground vehicles, aircraft, associated equipment, and fuel storage and distribution systems are needed to assess the ability to meet desired and/or required operational performance and to identify potential issues, as well as potential benefits, with the introduction and use of these fuels.

The Fischer-Tropsch (F-T) process has been used to produce Gas-to-Liquid (GTL) fuels since the 1920's [18]. Synthetic S-8 is a clean fuel with no sulfur or aromatics, which has historically been very costly to produce when compared with petroleum fuel. Since the mid-1990s, the world's major energy companies have started to develop modern F-T processes that are less expensive to build and operate. F-T synthetic fuels using this technology should result in reduced exhaust emissions from military diesel engines,

including reduced diesel exhaust particulate matter [6-11, 18]. These fuels also demonstrate low lubricity, which can be improved with military approved lubricity improvers. [8, 18]

Modern diesel engines are designed for commercial applications, and their base calibrations are based on the use of diesel fuel, not military fuel. Hence, operating standard engines with S-8 or any other alternative fuels might not lead to optimal engine performance. Modern CI engine technologies with electronic control units make dual-use calibrations viable; however, better understanding of the fundamental effects of alternative fuels on engine operation is required before control strategies can be developed. Given the recent focus on alternative commercial diesel fuels, such as synthetic diesel or biodiesel, correlating fuel properties of various fuels with engine performance and durability has broad interest.

This paper reports the long term engine performance and endurance of a compression ignition (CI) engine, which is used to generate power utilizing the two fuels, namely ULSD and synthetic fuel (S-8). These findings will help to better understand how these fuels perform in a CI engine generator set that is designed for military and emergency situations. Few reports exist to describe use of synthetic fuel in CI engines [10, 12]. Most of these reports utilize synthetic diesel fuel blended with petroleum diesel fuels such as ULSD and with altered engine calibrations [10]. The use of unblended S-8 on diesel engines has not been reported. In this study, both fuels were put through static load endurance and load transient tests. Engine operating parameters such as injection pressure and injection timing were kept constant for both fuels. At the completion of each run, the used lubrication oil was collected and analyzed to understand the effects each fuel had on engine part wear and on oil degradation.

2. Experimental Section

2.1 Evaluation of Fuel Properties.

The ULSD was additized for winter conditions. To eliminate batch to batch variations, 700 gallons of ULSD was purchased and stored in a stainless steel container.

Seven hundred gallons of synthetic fuel (S-8) was provided by the National Automotive Center, U.S. Army, Warren, Michigan. S-8 was not additized when received, but 60 ppm of a corrosion inhibitor/lubricity improver (CI/LI) was added upon arrival. Several important fuel properties were evaluated using the appropriate ASTM test methods and are given in Table 1. Testing procedures were conducted according to the relevant ASTM test methods. The densities of both fuels were measured as a function of temperature and these correlations were later used to calculate the brake specific fuel consumption (BSFC).

2.2 Engine Performance Evaluation

The test system contains an inline five cylinder diesel engine (3.0 L displacement, 3.4 x 4.1 inch bore and stroke), in conjunction with a 50 kW generator. An external load bank was coupled to the genset (generator engine set) to control loading of the engine. The engine has a mechanically governed unit pump fuel-injection system that is calibrated for Diesel #2 fuel. This was not altered throughout the testing. The intake is a turbocharged-aspirated engine with a compression ratio of 19.1:1 [19] and no exhaust gas return (EGR). The exhaust system has no after-treatment devices but was modified to incorporate an inline smoke meter chamber for opacity and smoke density measurements. The engine was instrumented with two turbine type flow meters in both supply and return fuel lines. These flow meters were calibrated for each fuel type depending on the viscosity values of the fuel being run. The integrated resistive thermal detectors (RTDs) in the flow meters measure the temperatures at the supply and return fuel lines. Using these two flow meters and with the help of temperature–density correlation, the BSFCs were calculated. In addition, two pressure gauges, each at the supply and return fuel lines and a differential pressure gauge across the fuel filter were installed. The exhaust gas temperature was also recorded using a K-type thermocouple.

Fuel was supplied to the engine by a tank with about a 200 gallon capacity. A hand pump was used to drain fuel in between fuel changes. For every fuel change, the fuel lines were cleaned, and the engine was left to run for at least two hours to stabilize on the new conditions.

The generator outputs an electrical load in three phases at 208 volts and 60 Hz utilizing a permanent magnet brushless rotating field. The generator is linked up directly to the engine from the flywheel of the engine to the clutch of the generator, and the frequency of the generator (60 kHz) was kept constant by the constant 1800 RPM of the engine.

The load bank electronically loads the genset with a manually selected stepped load. The load is dissipated as heat through an internal heat exchanger that has a controlled upper set point to prevent overheating of the load bank. Generator power, frequency, voltage, and current can be obtained using the data display meter of the load bank.

2.3 Data Acquisition and Engine Performance Parameters

Data was procured using two methods. Data was recorded manually at certain time intervals from the analog display panel used to monitor the genset. Oil pressure, engine coolant temperature, and engine runtime were all monitored utilizing this method. The second method utilized a controller with data being input from two flow meters, two temperature probes (RTDs), pressure gauges for the fuel input and return lines, a differential pressure gauge across the fuel filter, and a temperature probe to monitor the exhaust temperature. The voltage, power, amperage, and frequency data of the generator measured from the load bank were also recorded using software with a data acquisition frequency of 10 Hz. The data were collected at every five seconds and 100 data points were averaged. The BSFC in kg/kW-hr and brake thermal efficiency (BTE) were calculated to evaluate the engine performance during the 240 hours of engine testing with each fuel.

2.4 Testing Protocol

Both fuels were tested using the same testing matrix: an endurance test of total 240 hours, about eight hours per day at 60% of full capacity or 30 kW load; and a transient load testing of 20, 30, and 40 kW for two hours runtime were performed. A 240 hour endurance test was conducted under the military guidelines of MIL-STD-705C, Method 690.1d [20]. The startup procedure calls for the engine to be started with no load and run for an engine temperature and generator voltage stabilization period of 5 minutes. After

the 5 minutes, a load of 30 kW (60%) is applied and run for 8 hours. The time taken to reach the rated voltage and frequency after starting the generator is then recorded. The shutdown procedure calls for the 30 kW load to be turned off, and then run the engine for 5 minutes with no load, and finally shut off the engine. During this procedure, the following parameters were monitored and recorded: fuel supply and return line flow rates and temperatures; exhaust temperature; load bank frequency, power, voltage, and amperage; oil pressure; and coolant temperature. Ambient temperature, pressure, and relative humidity were also recorded. The baseline fuel, ULSD, was run for 8 hours after completion of S-8 testing in order to assess any performance degradation due to S-8 testing.

After the endurance run of each fuel was completed (240 hours), a transient load analysis was also run on the genset. The same startup and shutdown procedures for the endurance testing were used, but the load was varied to three different loads: 20 kW, 30 kW, and 40 kW, two hours each. The same parameters of the endurance performance were recorded, and the transient load analysis was repeated 3 times for each fuel.

2.5 Lubricating Oil Analysis

After each fuel test run was completed, the engine oil, oil filter, and fuel filter were changed with a sample of the used lubrication oil saved for testing and analysis purposes. Five ASTM methods were conducted on the used lubrication oil to test for any degradation and variation in physical properties and chemical composition. The lubricating oil used for ULSD testing was CJ-4 low ash synthetic oil while John Deere Plus 50[®] 15W40 synthetic blend engine oil was used during S-8 testing in accordance with manufacturer guidelines. The five methods are as follows: ASTM D 445-Kinematic Viscosity at 40°C and 100°C, ASTM D 43790-Total Base Number (TBN), ASTM D 3524-Diesel Fuel Dilution in Used Lubrication Oil, ASTM D 5185-Free Metal Analysis, and ASTM D 1796-Soot and Solids Testing Measurement. Most of the testing, with the exception of the free metals analysis, was conducted at an ISO 9001:2000 registered laboratory in Detroit, Michigan. The wear metals analysis testing was conducted utilizing inductively coupled plasma (ICP-OES) in accordance with ASTM D 5185.

3. Results and Discussions

3.1 Fuel Properties Analysis

As previously mentioned, the genset was tested with two fuels: Ultra-low sulfur diesel (ULSD) and synthetic fuel (S-8). Table 1 is a list of the properties of the fuels used for testing. These results are consistent with previously published properties of ULSD [10] and S-8 [21, 22]. S-8 has many fuel properties comparable with those of ULSD, and is also within the limits prescribed by ASTM D 975, specification for diesel fuels. It should be noted that the wear scar diameter of S-8 (with CI/LI additive per MIL-PRF-25017), as determined by High Frequency Reciprocating Rig (HFRR) per ASTM D 6079 was 680 μm , which does not meet the lubricity specification for the engine (450 μm maximum) used in this study or the requirement for diesel fuel (520 μm maximum). Although the ASTM D 6079 test method is for diesel fuel, not designed for jet fuel, this test method was used to evaluate the lubricity requirement of the diesel engine. Thus, 60 ppm CI/LI was added to reduce the HFRR wear scar diameter below 450 μm . This is necessary to prevent any wear of fuel injection systems. The relatively higher cetane number (shorter ignition delay) of synthetic S-8 fuel can be attributed to primarily straight, long chain hydrocarbons and lack of aromatic components (100 % C7 – 18 alkanes according to the certificate of analysis provided by the manufacturer). The cetane number affects cold-starting, combustion noise, and exhaust emissions. A fuel with lower cetane number can shift the timing of combustion considerably, especially at high speed – light load operating conditions, and this might lead to incomplete combustion and elevated emissions [8].

Both the viscosity and the density of S-8 are lower than those of ULSD. Viscosity and density of a fuel depend on the composition of fuel. ULSD, with a relatively higher molecular weight of aliphatic hydrocarbons and about 30% of aromatic compounds, shows higher viscosity and density than S-8. In diesel engines, fuel is usually injected into the combustion chamber using a volume based metering system. With such systems the fuel with lower density will yield lower engine power. The density of the fuel can

also have a direct effect on the build-up of fuel pressure in the injection system and a consequent effect on the dynamic start of fuel injection [23]. Compensating for the effect of density on specific power involves adjustment of injection pulse width (duration). This injection pulse width also depends on the fuel's lower heating value. The viscosity of fuel may affect the performance of the fuel injection pump and the injection system. Lower viscosity may lead to an increase in leakage losses from the pumping elements, and thus might cause a reduction in the amount of injected fuel quantity. Viscosity of the fuel also has an effect on the atomization and spray patterns of the fuel injectors, which can strongly affect the performance of an engine [8].

Another important property of a fuel which affects the injection characteristics is the volatility. The volatility of the fuel is characterized by the distillation curve (ASTM D 86) or boiling point range. In the ASTM D 86, the distillation characteristics are generated by noting the temperature at which a certain fraction of the fuel is boiled off. For example, the T90 value given in Table 1 is the temperature at which 90% of the fuel sample is boiled off. The highly volatile fraction of fuel has a tendency to evaporate before fuel gets into the injectors. The complete distillation curves obtained for ULSD and S-8 are shown in Figure 1.

3.2 Long Term Engine Performance

3.2.1 Fuel Consumption and Thermal Efficiency

Both ULSD and S-8 were each tested on the genset for 240 hours, at an applied load of 30 kW (60% of full load). The time required to reach the rated voltage and frequency of the generator after starting the engine (method 608 in MIL-STD-705C) was between 9 to 15 seconds for ULSD and 6 to 11 for S-8, depending on ambient conditions. It should be noted that the ambient temperatures during S-8 testing were significantly higher than those of ULSD testing. When the temperature was below -15 °C, the engine needed to warm up using block heaters for proper start-up of the generator, since this engine was not equipped with glow plugs.

The following equations were used to calculate the BSFC and BTE:

$$\text{BSFC (kg/kW-hr)} = \text{Fuel Consumption Rate (kg/hr)} / \text{Power (kW)}$$

$$\text{BTE} = 3600/\text{BSFC (kg/kW-hr)} * \text{LHV (kJ/kg)}$$

The volumetric fuel consumption was measured using the two turbine type flow meters installed in the supply and return fuel lines, which were re-calibrated for the densities of the fuel for each temperature.

BSFC, the ratio between mass fuel consumption and brake effective power, is inversely proportional to thermal efficiency for a given fuel. Thermal efficiency is the ratio between the power output and the energy introduced through fuel injection, with the latter being the product of the injected fuel mass flow rate and the lower heating value. The BSFC and BTE during a typical day's run are given in Figure 2a. About eight hours of continuous testing were performed each day. Data were collected in 5 second intervals and each data point in Figure 2a contains average of 100 data points. As shown in Figure 2a, both S-8 and ULSD had relatively stable BSFC and BTE values during eight hours of testing. S-8 had lower fuel consumption, and therefore higher thermal efficiency. S-8, however, had relatively larger variations compared to ULSD. The average BTE for S-8 is 0.326 ± 0.006 and is 0.287 ± 0.002 for ULSD. These variations of fuel consumption and thermal efficiency can be attributed to the properties of S-8 and will be described in detail in a later section.

BSFC and BTE of the generator running on ULSD and S-8, as a function of accumulated run time, are shown in Figure 2b. The average BSFC and BTE during the 240 hours of ULSD run were 0.308 ± 0.013 kg/kW-hr and 0.287 ± 0.002 , respectively. This BTE is the overall efficiency of the generator and the engine. The generator efficiency, according to the manufactures, is within 90-95%. Considering this, the BTE of the engine is between 0.313 and 0.327 which is typical for a CI engine of this class [1]. A slightly improved (lower) fuel consumption and hence increased BTE was observed for ULSD as a function of run time. For example, the average BSFC and average BTE during the first 100 hours are 0.315 kg/kW-hr and 0.277 respectively. The average BSFC and BTE values during the last 100 hours are 0.309 kg/kW-hr and 0.283 respectively. This 2% thermal efficiency increase can be attributed to the conditioning (break-in) of the

new engine, and suggests that the generator performance did not degrade during the specified test period.

On the other hand, average BSFC and BTE during the 240 hours of S-8 run were 0.267 ± 0.019 kg/kW-hr and 0.326 ± 0.006 , respectively. As shown in Figure 2b, lower BSFC, and hence higher BTE compared to ULSD, was observed when the engine was running using S-8. The lower BSFC (gravimetric) of S-8 can be attributed to the lower density of S-8 compared to ULSD (Table 1). This result is consistent with the results of Abu-Jrai et al. [24], who reported improved fuel consumption when using lower viscosity GTL fuel. S-8 with lower viscosity results in increased fuel losses during the injection process; ULSD with higher viscosity results in a slower evolution of pressure and, thus, a retard in fuel injection timing, which normally decrease fuel consumption. Also it is reported that at a given injection pump setting, fuels with higher densities have increased mass flow rates [25]. A trend of slightly decreasing BTE during 240 hours of S-8 testing can be seen in Figure 2b. This could be due to internal leaking of S-8 within the fuel delivery system since S-8 has been reported to have compatibility problems with sealing materials [11]. However, the average BSFC and BTE for ULSD after completion of S-8 run were 0.296 kg/kW-hr and 0.299 kg/kW-hr, respectively, which is similar to the values obtained for initial 240 hours of ULSD testing. This confirms that no permanent damage was done to the engine during the 240 hours of S-8 testing, based on ULSD data before and after the S-8 tests.

The BSFC and BTE for ULSD and S-8 under different engine load conditions are given in Figure 3. S-8 shows lower specific fuel consumption than ULSD at every level of the engine loads. The highest specific fuel consumption and hence the lowest thermal efficiency for both ULSD and S-8 were observed at 20 kW load conditions. The highest BSFC difference for S-8 compared to ULSD, however, was observed at 30 kW loads when ULSD was 11.7 % higher than S-8. The highest BTE increases between loads were from 20 to 30 kW for both ULSD (17.2%) and S-8 (23.6%). The BTE increase from 30 to 40 kW is 7.8% for ULSD and that for S-8 is only 2.3%.

3.2.2 Exhaust Gas Temperature and Smoke Opacity

Figure 4a shows the exhaust gas temperature (EGT) versus engine run time for a typical single day of engine testing with ULSD and S-8 at 30 kW loads. The ambient temperatures for the two tests shown in Figure 4a are 15 °C for S-8 and -3 °C for ULSD. The EGTs recorded for each day of testing showed that the equilibrium EGT is independent of the ambient temperature but varies with fuel type. S-8 shows about 50 °C higher EGT compared to ULSD. This could be due to the more complete combustion of S-8, which is consistent with the higher BTE. Figure 4b presents the EGT as a function of accumulated engine operating hours. No significant change was observed for S-8 and slightly increased EGT was observed during 240 hours of ULSD testing.

The average smoke opacity value recorded after an hour of engine running was 13 ± 4 % for ULSD and 7 ± 3 % for S-8. Continuous smoke opacity measurements were not possible with this in-line smoke meter due to water condensation on the detector. The lower smoke opacity of S-8 can be attributed to several factors, (a) the cleaner, aromatic and sulfur-free nature of S-8 compared to ULSD, (b) the lower initial boiling point of S-8 with respect to ULSD, which leads to easier fuel evaporation at relatively low starting temperatures, and (c) the lower viscosity of S-8 at low temperatures which increases the rate of spray atomization [26]. All of these phenomena lead to lower smoke opacity for S-8.

4. Generator Stability

The military guidelines for generator testing (MIL-STD-705C) list several methods to test generator stability. Method 608.2a describes the long term frequency and voltage stability and method 619.2c describes the % voltage dip and rise for a rated load test. Figure 5a displays the generator power and frequency traces for eight hours of testing when the engine was running on ULSD and S-8. The major difference observed in S-8 testing compared to ULSD is that the frequency and power output of the generator are not as stable as those of ULSD. S-8 gives an average frequency value of 60.27 ± 0.039 Hz while ULSD gives 60.18 ± 0.008 Hz. S-8 gives an average power value of 29.59 ± 0.14 kW while ULSD gives 29.45 ± 0.04 kW at 60% load. This instability of power and frequency may be due to the fact that the engine calibration parameters such as, injection pressure, and injection timing, were optimized for ULSD but not for S-8. Thus, S-8,

which is more volatile (Figure 1) than the ULSD, can partially vaporize either in the unit injection pump or the line from the injection pump to the injector. Therefore, each injection will have a different amount of fuel, (either slightly higher or lower), causing the engine to oscillate in speed (frequency) and in load. Based on the distillation curves presented in Figure 1, the initial boiling point of S-8 is about 20 °C lower than that of ULSD and 5% of S-8 boils off at 167 °C (at 1 atm pressure), compared to 201 °C for ULSD. Another possible explanation can be attributed to the lower density of S-8. Under the same load conditions, the engine requires higher mass flow of lower density S-8 compared to ULSD. Thus, the instability could be a combination of higher volatility and lower density of S-8. It should be noted that no physical damage to the injectors were observed after S-8 testing, suggesting that there were no cavitations of S-8 vapors inside the injectors. These power and frequency variations did not damage any part of the fuel injection systems, since ULSD testing just after 240 hours of S-8 testing did not show any instability.

The generator power and frequency for ULSD and S-8 run as a function of accumulated engine run time are presented in Figure 5b. As can be seen from this figure, both power and frequency are more stable for ULSD throughout the 240 hours of testing, compared to S-8 testing. The day to day variation of both generator power and frequency are larger for S-8 compared to ULSD.

The variation of frequency and power as a function of engine run time under different 40, 30 and 10 kW load conditions are given in Figure 6. As shown in Figure 6a, the oscillation of frequency and power are greatest when the generator is fueled with S-8 at high load. At a 40 kW load, the generator produced an average frequency of 60.33 Hz with minimum and maximum frequencies of 59.07 and 61.59 Hz, respectively. These values are closer to the acceptable range of 58-62 Hz as specified by the U.S. Army for 60 kW tactical quiet generator sets [27]. The mass flow rate effect due to differences of densities is greater at higher loads. On the other hand, the frequency and power traces for ULSD remained stable for different load conditions (Figure 5b).

The currents (A) at terminals A, B and C, and the voltages (V) across terminals A-B, B-C and, C-A for a typical 250 minutes of engine run time are presented in Figure 7. Under a steady 30 kW load, the generator produced 82.3 A current (average) and 205.4 V

with ULSD (Figure 7a), while S-8 produced an average current of 82.44 A and average voltage of 206.69 V. Initial spikes of current at all 3 terminals were observed when the load changed from no load to 30 kW load. For ULSD, the voltage stabilized instantaneously after an initial voltage drop from no load to 30 kW load. However, it took longer for S-8 to stabilize the voltage to the rated value from no load to the 30 kW load. The percent voltage drop measured according to method 619.2c, for both ULSD and S-8 from no load to 30kW load is less than 0.04%. These generator performance parameters such as percent voltage drop, frequency, and voltage stability are within the limits given by the military specifications [27], but they approach out of the specified range when S-8 was utilized at higher load conditions.

5. Used Lubricating Oil Analysis

Viscosity, total base number (TBN), diesel fuel dilution and soot testing of both sets of the used versus fresh lubrication oil are presented in Table 2. The lubricating oil used for ULSD testing was CJ-4 low ash synthetic oil while John Deere Plus-50® 15W40 synthetic blend oil was used for S-8 testing, which accounts for differences in the baseline oil properties.

No major deterioration in the viscosity, TBN, fuel %, or soot % was observed for either fuel. Less than 1% oil dilutions were observed for both ULSD and S-8. Interestingly, there is a decrease in viscosity at 40°C (14% decreases with ULSD versus 5% decrease with S-8), in contrast to the reported tendency for oil to increase in viscosity over time.

A greater decrease in the TBN was observed for oil used with S-8 than that used with ULSD. The TBN value for used oil after S-8 testing was 7.5 and that of ULSD was 6.8. However, both values are above the recommended replacement levels of 3.0 mg KOH/g.

The wear metal analysis results can be seen in Table 3. As with the other tests, the used lubrication oils were tested against fresh oil, but added into this test was the free metal analysis of both the ULSD and S-8 fuels. This analysis was conducted to see if any metals present in the fuel were present in the used lubrication oil, along with any wear metals from the use of the oil. The major elements of interest are Al, Cr, Ni, Fe, Sn, Co and Mo which are present in many engine parts such as, pistons, bearings, crankshaft,

gears and compression rings [28]. The most abundant metals found in additive packages in the oil are zinc and phosphorus, which come from Zinc Dithiophosphate (ZDP), and are used as an anti-wear package. As seen in Table 3, only Mo, Fe and B show significant increase in used lubricating oils. However these values (14 ppm – 19 ppm) are not high enough to be considered as possible wear. There does not seem to be a significant amount of wear as all the major components are well within the lower bound of the typical ranges for all of the runs.

6. Conclusions

The performance of a generator set fueled with ULSD and synthetic fuel S-8 was investigated. Better fuel consumption and hence higher thermal efficiency was observed for S-8 compared to ULSD. Engine performance degradation was not observed during 240 hours of ULSD and S-8 testing. Engine part wear was not observed for either ULSD or S-8 testing. The instability of generator power and frequency when using S-8 could be a potential problem for military and emergency power generation applications, especially at higher power demand situations. The data presented here help identify potential problems with the use of synthetic fuel, namely Synthetic Paraffinic Kerosene, in a compression ignition engine. Engine technologies with auto calibrating capabilities, which can compensate the physical property differences of various fuels, should be investigated.

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Tables

Table 1: Properties of ULSD and S-8

Property	ASTM Method	ULSD	S-8
Lubricity (μm)	D 6079	336.00	353.00
Cetane Number	D 6890	42.30	56.10
Cloud Point ($^{\circ}\text{C}$)	D 2500	-22.00	<-33.00
Pour Point ($^{\circ}\text{C}$)	D 97	<-33.00	<-33.00
Carbon Residue	D 4530	0.00	0.00
LHV (kJ/g)	D 240	41.50	41.80
Flash Point ($^{\circ}\text{C}$)	D 93	53.50	40.50
Viscosity (mm^2/s)	D 445	2.96	1.29
Distillation			
Temperature ($^{\circ}\text{C}$) (90% Recovered)	D 1160	304.00	248.00
Density (kg/L)	N/A	0.85	0.74

Table 2: Used Lubricating Oil Analysis

A large black rectangular redaction box covers the entire content area of the table, obscuring all data and headers.

Table 3: Analysis of wear metals in lubricating oil used during ULSD and S-8 testing. For comparison metals present in fresh oil, ULSD and S-8 are also presented. The concentrations are given in ppm.

Metal	ULSD	S-8	Fresh Lube Oil (ULSD)	Fresh Lube Oil (S-8)	Used Lube Oil (ULSD)	Used Lube Oil (S-8)
Ag	0.09	1.20	0.89	0.99	0.15	1.00
Al	0.00	0.27	1.00	0.00	0.09	5.00
B	4.94	2.31	0.00	5.36	19.11	80.00
Ba	0.46	0.50	0.00	0.46	4.80	3.00
Ca	0.93	0.50	1010.00	3490.00	1511.00	3310.00
Cr	0.00	0.00	0.00	0.02	1.00	0.90
Cu	0.58	2.35	1.00	3.17	5.36	1.89
Fe	3.59	5.71	2.00	4.98	27.09	17.33
K	0.59	0.46	0.00	0.78	2.52	2.70
Mg	1.32	0.00	746.00	752.10	753.20	689.00
Mn	3.97	2.31	1.00	4.06	4.76	2.56
Mo	0.53	0.00	1.35	1.26	14.02	13.07
Na	3.20	0.00	6.00	9.96	11.41	5.83
Ni	1.59	0.00	0.00	1.59	2.56	2.00
P	2.67	0.00	1120.00	1280.00	1234.00	1200.00
Pb	1.80	0.52	1.00	1.95	2.38	0.00
Sn	3.53	2.70	4.00	2.65	3.02	3.21
Ti	3.19	0.00	1.00	3.20	3.27	2.00
Zn	2.50	0.00	1200.00	1510.00	1160.00	1500.00

Figures

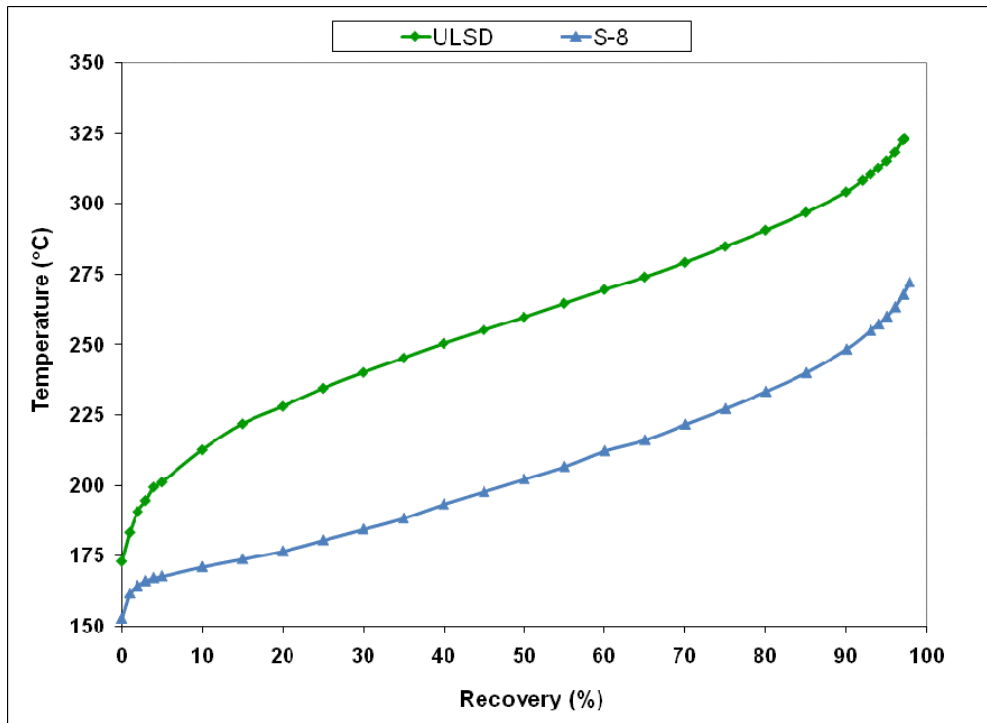


Figure1: Distillation Curves for ULSD and S-8 constructed using ASTM D 86 test method.

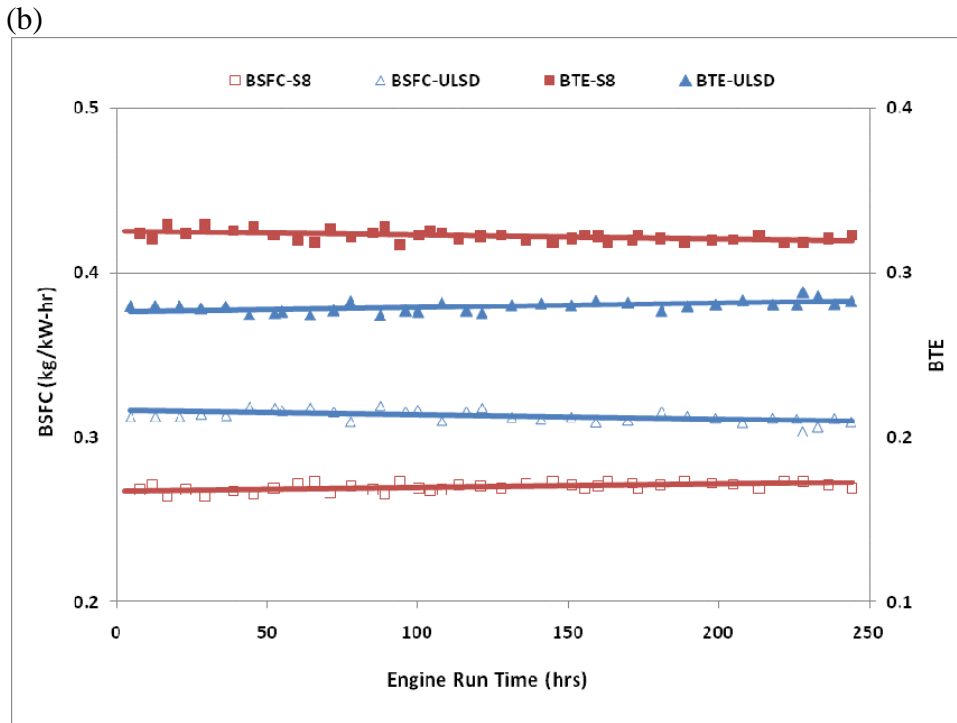
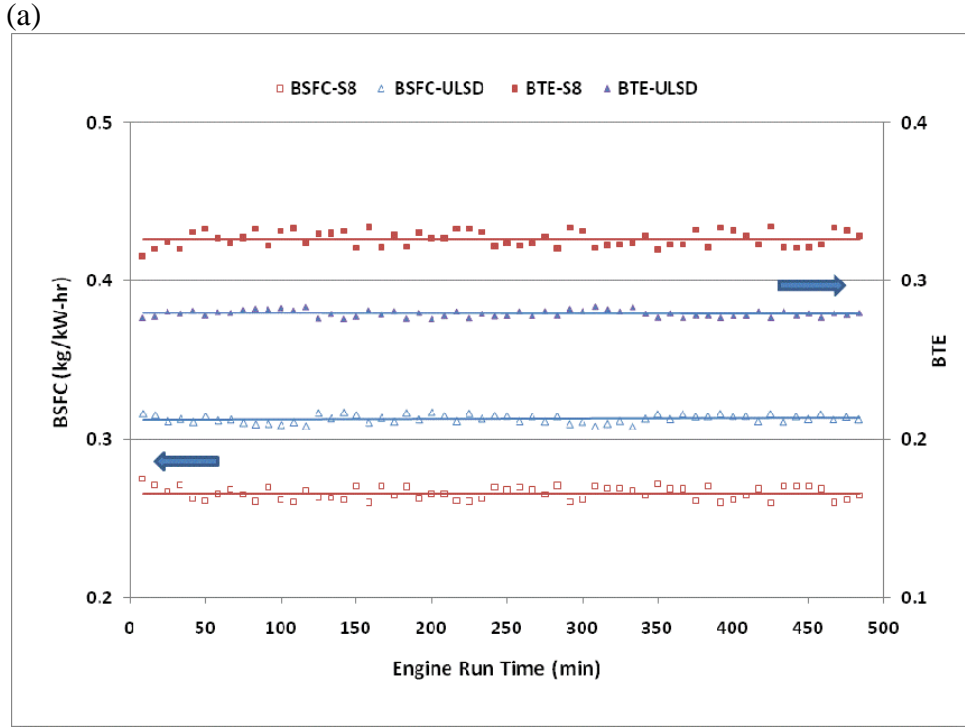


Figure 2: Comparison of fuel consumption and thermal efficiency of the engine fueled with ULSD and S-8; (a) variation during continuous eight hours run of a typical day, (b) as a function of accumulated engine runtime.

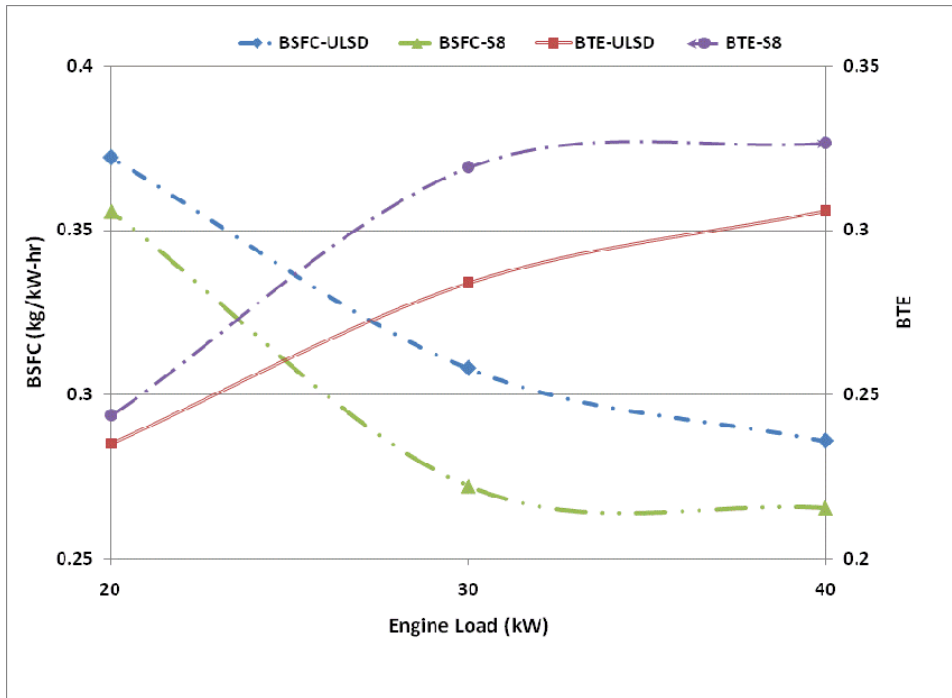
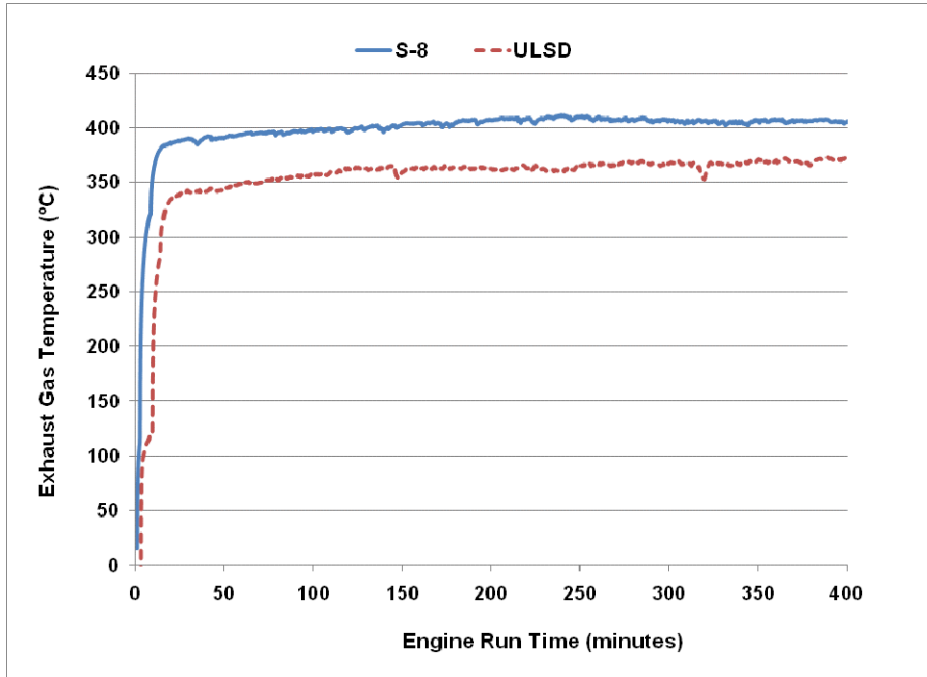


Figure 3: Specific fuel consumption and thermal efficiency of the engine at different load conditions for ULSD and S-8.

(a)



(b)

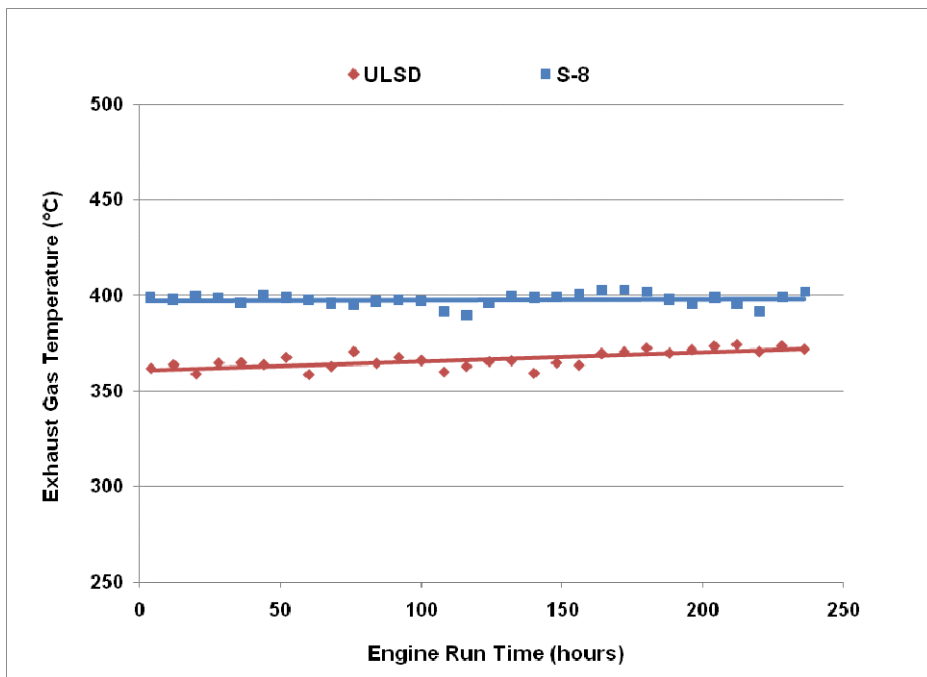
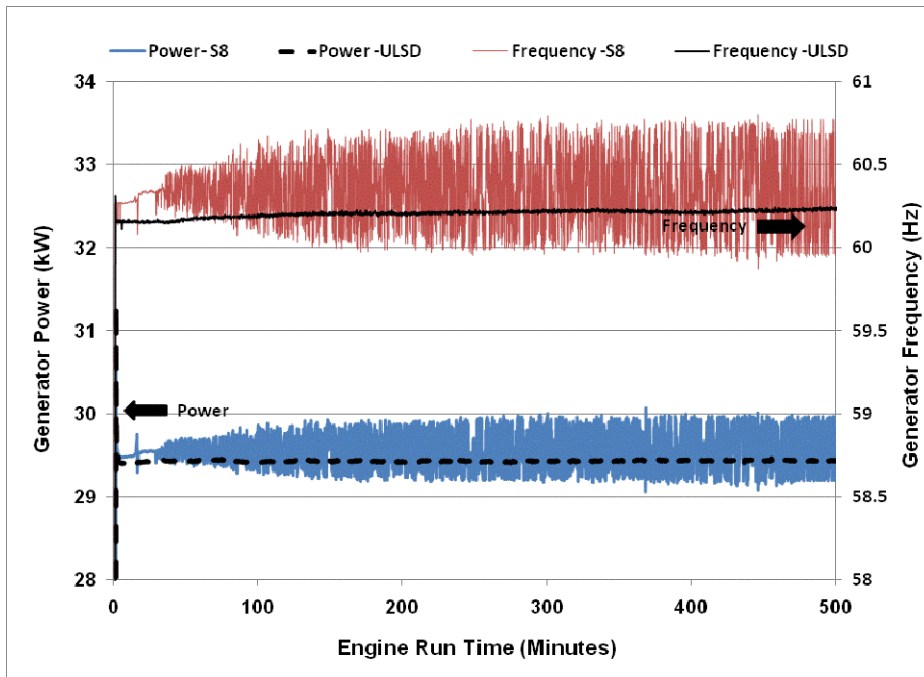


Figure 4: Exhaust gas temperature for ULSD and S-8 ; (a) variation during continuous eight hours run (b) as a function of accumulated engine runtime.

(a)



(b)

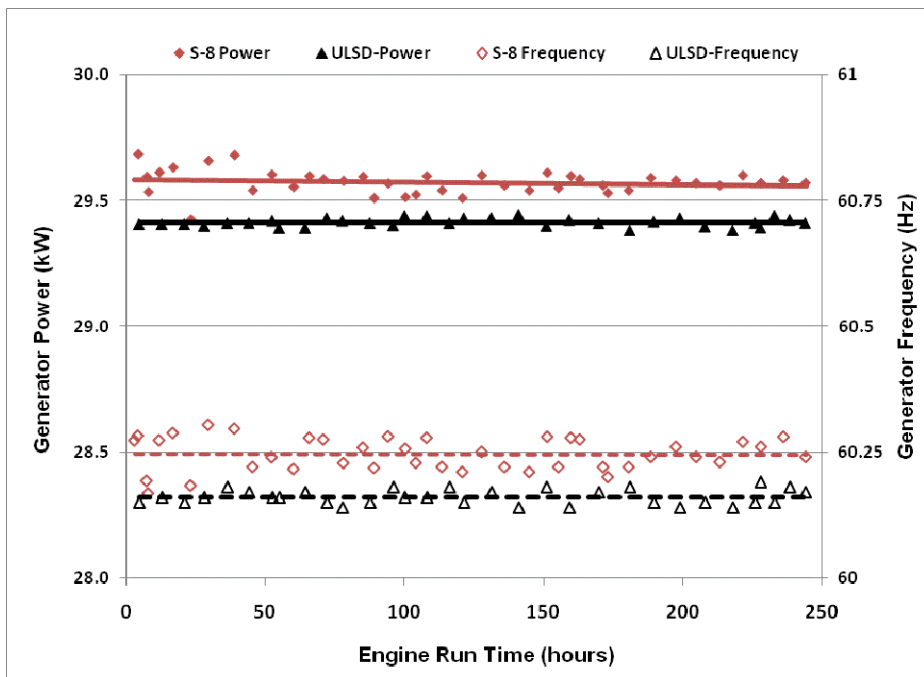
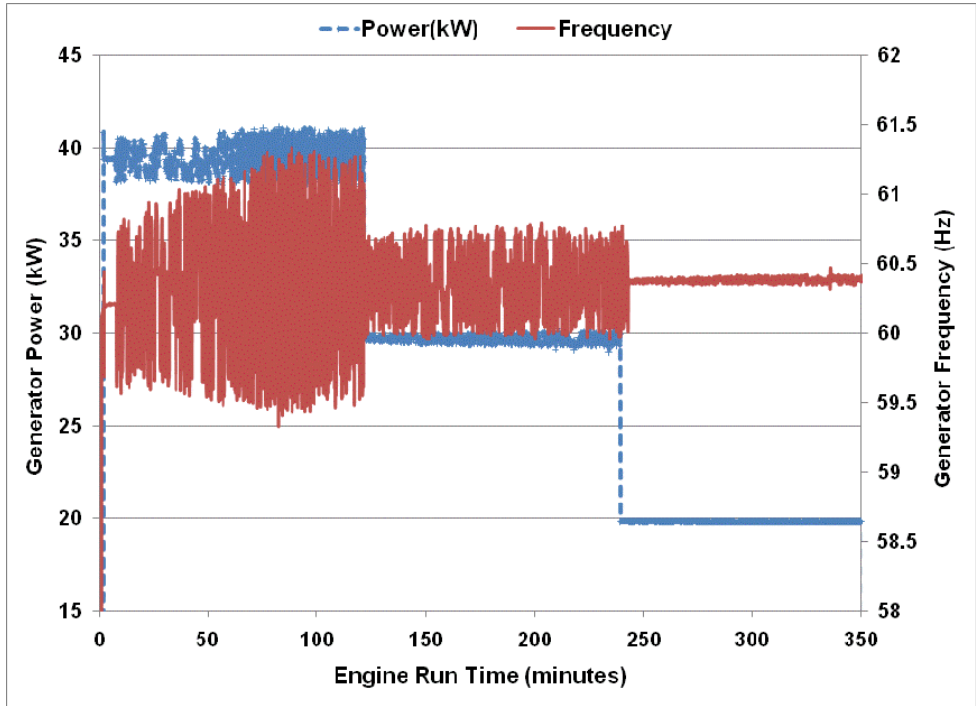


Figure 5: Frequency and power variations of the generator running on S-8 and ULSD (a) continuous eight hours of running time, (b) as a function of accumulated engine runtime.

(a)



(b)

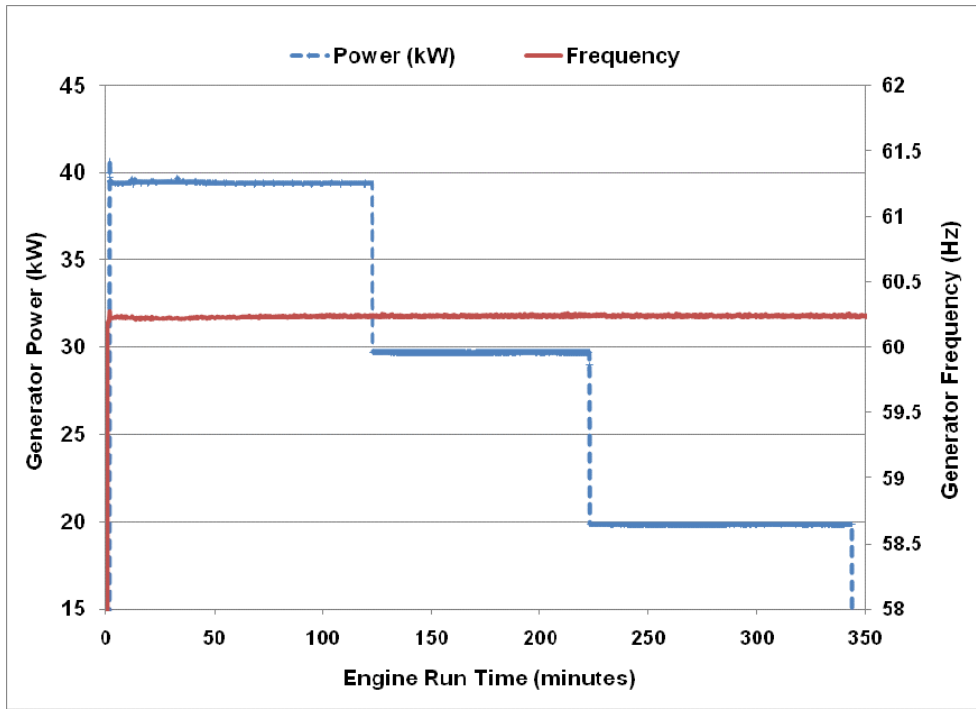


Figure 6: The variation of frequency and power as a function of engine run time under different load conditions, (6a) S-8 and (6b) ULSD.

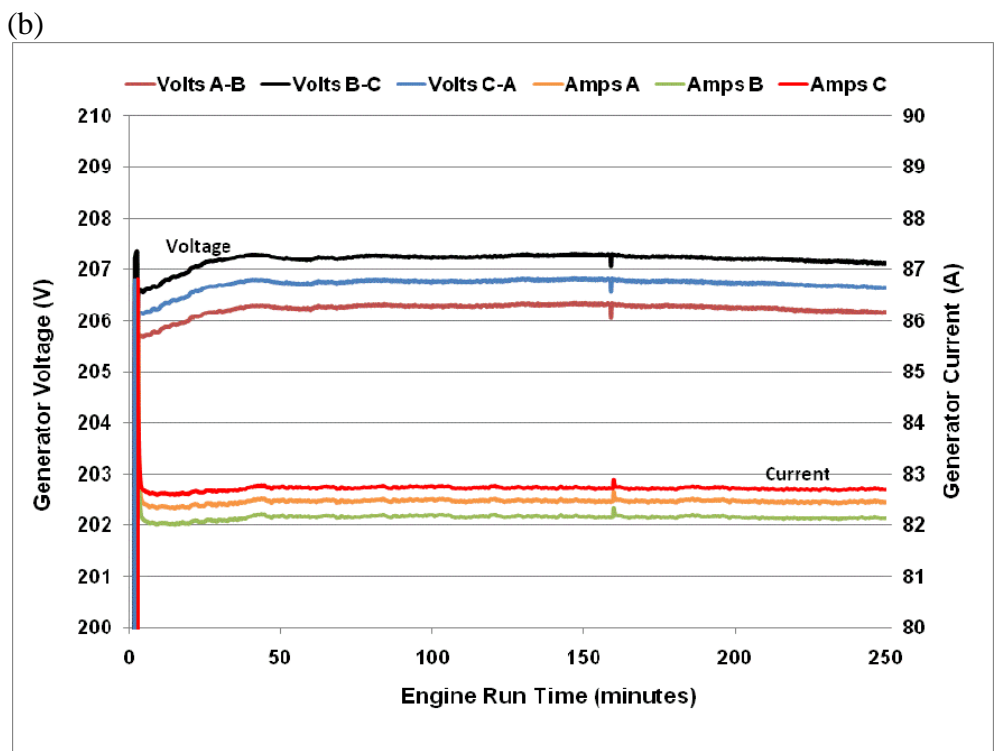
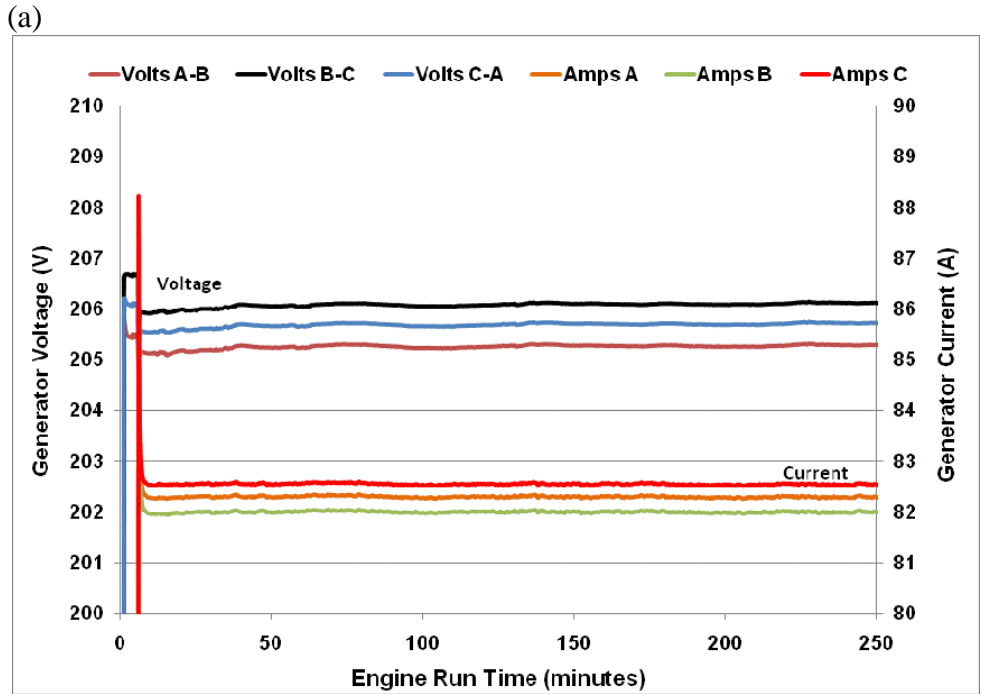


Figure 7: Voltage and Current variations of the generator running on ULSD (7a) and S-8 (7b) during four hours of running time.