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Engine Performance and Exhaust Emissions from a Diesel Engine Using Soy Bean Oil Biodiesel

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Abstract. *The objectives of this study are to evaluate the performance and relate exhaust emissions of biodiesel fuels derived from soybean oil and Standard no. 2 ultra low-sulfur diesel fuel, in a 3-cylinder YANMAR diesel engine. Engine power tests were conducted in accordance with SAE Standard Engine Power Test Code for diesel engines (SAE J1349 Revised MAR2008). Test fuels included Standard no. 2 diesel and four biofuels comprising 5%, 20%, 50% and 100% soybean oil biodiesel. Nitrogen oxides (NO_x), carbon monoxide (CO), and sulfur dioxide (SO_2) emissions were measured for all the test fuels using an Enerac™ model 3000E emissions analyzer. Based on the results of the experiments performed, the peak power produced using different blends of Soy bean oil biodiesel has no significant difference compared to that of the petroleum diesel. However, the brake-specific fuel consumption tends to increase as the percentage of biodiesel in a blend increases. Such an increase can be best described by the B50 SME and B100 SME test fuels. Furthermore, the relationship between pollutant concentrations in diesel engine exhaust and the* *percentage of soy bean oil biodiesel in fuel blends was also determined. There was a significant reduction in the emissions of pollutant concentrations (i.e. NO_x and CO) as the percentage of biodiesel in a blend increased.*

Keywords. *Biodiesel, Biodiesel blends, Biofuels, Diesel engine, Engine exhaust emissions, Performance, Soy Methyl Ester.*

Introduction

One of the major advantages of biodiesel fuels is the fact that it can be used in existing diesel engines with a modest amount of impact to an engine's operating performance. However, in some cases, engine performance may not be as comparable when using biodiesel to petroleum diesel. In such a case, it would depend on the oil feedstock being used. According to Hansen et al. (2006), torque loses 9.1% relative to Standard No. 2 Diesel from fueling the engine with 100% soybean biodiesel. Some fuel properties such as the degree of saturation of several oil sources may have an effect on the engine performance primarily due to the heating value differences, which will eventually have significant impact on the exhaust emissions.

According to the National Biodiesel Board (2006), one of the factors that affect vehicle fuel economy, torque, and horsepower is the fuel's volumetric energy content or its heating value. The heating value of a fuel is the amount of heat released during combustion. In the U.S., the heating value is usually expressed as British thermal units (Btu) per pound or per gallon at 60°F (International metric [SI] units are kilojoules per kilogram or per cubic meter at 15°C). For gross (high) heating value, the water produced by the combustion is assumed to be re-condensed to a liquid. For the net (lower) heating value, the water remains as a gas. Since engines exhaust water as a gas, the net heating value is the appropriate value for comparing fuels (NBB, 2006). The heating value of biodiesel fuel is much less variable than that of petroleum diesel. And if a biodiesel fuel meets the ASTM D 6751 standards, the heating value is more dependent upon the feed stocks used than the particular process.

The objectives of this study are the following: (1) Evaluate the performance and (2) relate exhaust emissions of biodiesel fuels derived from soybean oil and Standard no. 2 ultra low-sulfur diesel fuel, in a 3-cylinder YANMAR diesel engine.

Materials and Methods

The engine performance and exhaust emissions testing were conducted at the Bio-Energy Testing and Analysis Laboratory (BETA LAB) of the Biological and Agricultural Engineering Department, Texas A&M University, College Station, Texas. The facility has the instrumentation needed to measure some of the regulated emissions, such as Carbon Monoxide (CO), Carbon dioxide (CO_2), Oxides of Nitrogen (NO_x), Total Hydrocarbons (THC), and Sulfur dioxide (SO_2).

Test equipment

The BETA LAB has a 3-cylinder Yanmar 3009D diesel engine rated at 14.2 kW (19 Hp), which was used for this research (Figure 1). Table 1 lists the general specifications of the test engine. The engine load was controlled using a water-cooled eddy current absorption dynamometer with a Dynamatic® EC 2000 controller. The maximum braking power of the dynamometer was rated at 22.4 kW (30 hp) at 6000 rpm.

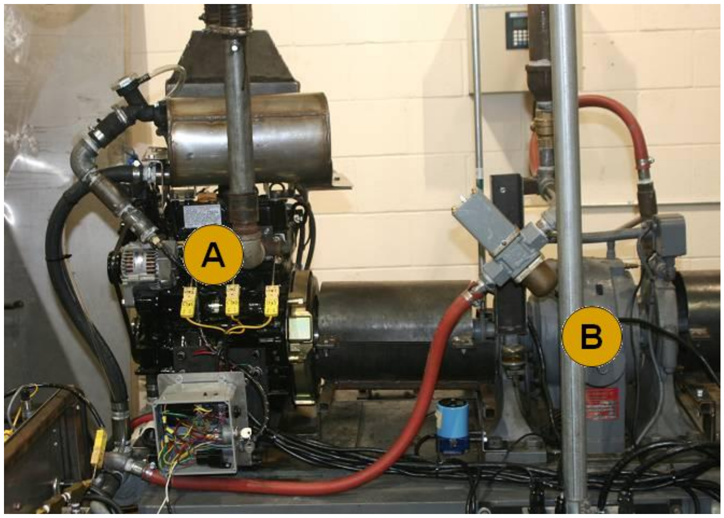

Figure 1. The Dynamometer test system showing (A) 14.2 kW diesel engine, and (B) the dynamometer.

Table 1. Specifications of Yanmar 3009D diesel engine

Rated Power	14.2 kW @ 3000 rpm
Number of Cylinders	3
Bore	72 mm
Stroke	72 mm
Displacement	0.879 L
Compression Ratio	22.6:1

Test Fuels

Commercially available soy methyl ester (SME) and ultra low-sulfur diesel were tested. They were analyzed at the BETA LAB to determine if such fuels meet ASTM 6751 standard. Table 2 enumerates the properties of the test fuels. Fuels and fuel blends are as follows:

1. Standard No. 2 ultra low-sulfur diesel control fuel (REFDIESEL)
2. 100 percent soy methyl ester (B100 SME)
3. 50 percent soy methyl ester (B50 SME)
4. 20 percent soy methyl ester (B20 SME)
5. 5 percent soy methyl ester (B5 SME)

Table 2. Test Fuel Properties.

Fuel Property	Standard no. 2 ULS Diesel*	B5 SME	B20 SME	B50 SME	B-100 SME
Gross Heating Value, MJ/kg (Btu/lb)	44.18 (18994.05)	43.87 (18901.54)	43.23 (18624.19)	41.93 (180669.40)	39.88 (17144.75)
Cloud point (˚C)	-35	-34.75	-34	-32.5	-30
Flash Point (˚C)	128	131.5	142	163	198
Kinematic Viscosity (mm^2/s) @ 40˚ C	2.2576	2.3364	2.5596	3.258	4.3965
Density (kg/L at 21°C)	0.8445	0.8463	0.8515	0.8621	0.8796
Specific gravity (at 21°C)	0.8454	0.8472	0.8524	0.8630	0.8805
Acid number (mg KOH/g)	0.0373	0.0464	0.0739	0.1289	0.2204

* Ultra-low sulfur diesel

Data Acquisition Equipment and Exhaust Emissions Analyzer

Torque and engine speed data were collected using a NI LabView 8.0 program. Fuel flow was measured using a Model 214 Piston Flow Meter, and then transmitted using a Model 294 High Resolution, Linearized Frequency Transmitter (Max Machinery Inc., Healdsburg, CA).

Exhaust emissions, such as carbon monoxide (CO), carbon dioxide (CO_2), oxides of nitrogen (NO_x), and sulfur dioxide (SO_2), were determined with an Enerac™ model 3000E emissions analyzer. The emissions analyzer has a capability of 0 to 3500 ppm NO_x concentration measurement with an accuracy of ± 2% of reading. In addition, it also measures the ambient temperature, stack temperature, and O_2 concentration of the test room. Since the analyzer is new prior to this research, factory calibration was considered.

Experimental Method

Engine power tests were conducted in accordance with SAE Standard Engine Power Test Code for diesel engines (SAE J1349 Revised MAR2008). The experimental framework for this research was patterned to Powell's (2007) work. Baseline engine performance and emissions tests were performed using Standard no. 2 ultra low-sulfur diesel fuel. Variables such as air and relative humidity were carefully monitored. Fuel temperature was controlled as outlined in the test procedure. Tests were conducted in a systematically randomized order to prove that the fuel sequence is not significant to the results of the study. There were three blocks, with each block containing one set of tests for each fuel and fuel blend. The blocks are as follows:

Block 1 REFDIESEL, B50 SME, B5 SME, B20 SME, B100 SME, REFDIESEL

Block 2 REFDIESEL, B100 SME, B5 SME, B50 SME, B20 SME, REFDIESEL

Block 3 REFDIESEL, B5 SME, B100 SME, B50 SME, B20 SME, REFDIESEL

The BETA LAB is equipped with a NI LABVIEW program that can perform remote-based switching of fuel source. At each fuel change, the engine was warmed at idle speed on the new fuel for 10 minutes to purge remaining previous test fuel from the engine's fuel system. Then, the engine was ran at full throttle and prepared for the next performance testing.

In order to understand the effect of the biodiesel on engine efficiency, brake specific fuel consumption (BSFC) for B-100 SME and each fuel blend at peak brake power were measured and compared to the BSFC of the control fuel using statistical analyses, One-way Analysis of Variance (ANOVA) and Fisher's Least Significant Distance (LSD) procedures, respectively. Emissions results from the tests were then averaged.

RESULTS OF ENGINE PERFORMANCE TESTING

Basic engine performance from the test fuels was examined. All results presented in this research were obtained from the average of the three blocks of performance tests. Figure 2 shows the performance curves for the diesel engine using Standard no. 2 ultra low-sulfur diesel and B-100 SME. For the standard no.2 ultra low-sulfur diesel, the corrected peak brake power was at 13.4 kW (18.0 hp) at an engine speed of approximately 2965 rpm. Consequently, at an engine speed of 2390 rpm the peak torque was observed at 49.5 N-m (36.5 lb-ft).

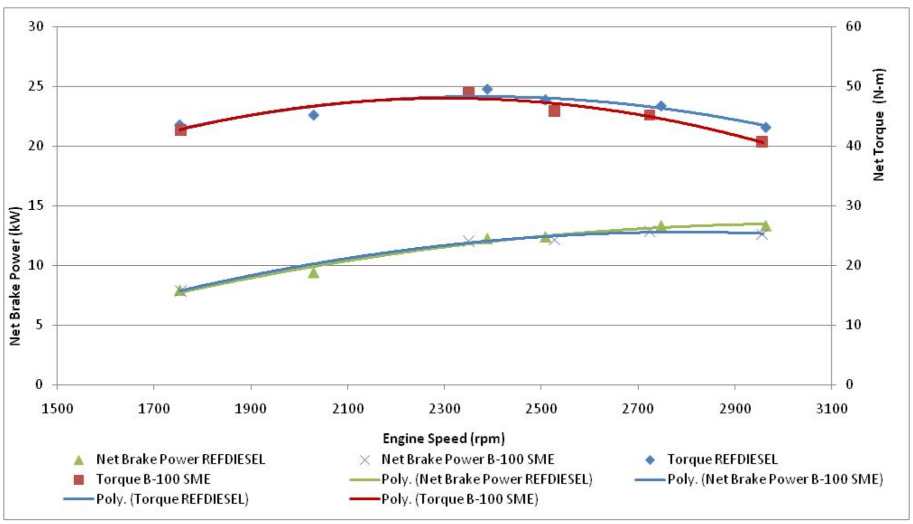

Figure 2. Performance curves of the 14.2 kW diesel engine using

Standard No. 2 Ultra low-sulfur diesel and B-100 SME.

It was also observed that the peak brake power was at 12.9 kW (17.3 hp) at 2725 rpm when B-100 SME fuel was used and it was 3.7% lower compared to the peak brake power using petroleum diesel. Since there were no modifications in the injection rates, such power loss may be attributed to the variation in densities and heating values of the test fuels.

The peak torque was observed at 48.9 kW (36.1 hp) at 2350 rpm, which may be comparable to petroleum diesel with 1.2% change. Hansen et al (2006) and Peterson et al (1995), measured the engine performance of a diesel engine using soybean oil biodiesel, and they found similar trend reductions in peak torque when compared to Standard no. 2 diesel fuel.

Brake specific fuel consumption (BSFC) is a good measure of an engine's efficiency. As shown in Table 3, B50 SME and B100 SME have higher BSFCs compared to the reference diesel fuel. The increase in BSFCs of these fuels is understandable since the biodiesel fuels have heating values that are about 5.1% and 9.7% less than that of the reference diesel. These results were in the same trend with the studies of Monyem (1998), McDonald et al (1995), and Canakci and Van Gerpen (2003), who ascertained that the BSFCs for biodiesel fuels were about 13% to 14% higher than no.2 diesel fuel.

Table 3. Average values and percentage changes in BSFC.

Test Fuel	BSFC (g/kW-h)	% change in BSFC
REFDIESEL	285.244389	-
B5 SME	281.6889697	- 1.24645
B20 SME	284.0386352	- 0.42271
B50 SME	294.7444105	3.330485
B100 SME	307.5007245	7.80255

The Box plots of the brake specific fuel consumption at peak brake power for B-100 SME and its blends with REFDIESEL are shown in Figure 3. One-way ANOVA and Fisher's LSD confirmed that there are significant differences in BSFC's between B100 SME and its blends to REFDIESEL. Again, these differences can be attributed to the lower heating values of the biodiesel and its blends.

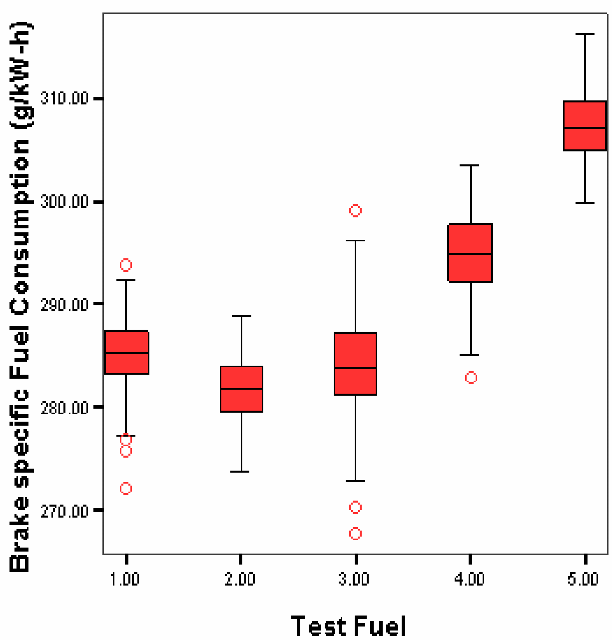

Figure 3. Box plots of the BSFCs (g/kW-h) of (1) REFDIESEL, (2) B5 SME, (3) B20 SME, (4) B50 SME, and (5) B100 SME test fuels.

RESULTS OF EMISSIONS TESTING.

Nitrogen oxides (NO_x), carbon monoxide (CO), and sulfur dioxide (SO_2) emissions were measured for all the test fuels using an Enerac™ model 3000E emissions analyzer. Total hydrocarbons (THC) emissions were not measured since the THC sensor of the analyzer malfunctioned prior to testing. Figure 4 shows the amount of NOx produced at different engine speeds for all biodiesel fuel blends including the Standard no. 2 ULS diesel as the reference fuel. Based on the graph, a general decreasing trend was observed for NO_x emission as the engine speed was increased from 2700 rpm to 3200 rpm. The NOx emissions of the reference fuel dropped by approximately 170 ppm while 160 ppm drop was noticed for B-100 SME.

The NO_x emissions were higher for B100 SME and blends than the standard no. 2 ULS diesel fuel. Compared to the reference fuel, the NO_x emissions of B50 SME and B100 SME were increased by 5.8% and 5.6%, respectively. Such increase may be associated to the oxygen content of the biodiesel since it would have more oxygen to add up to the NO_x formation.

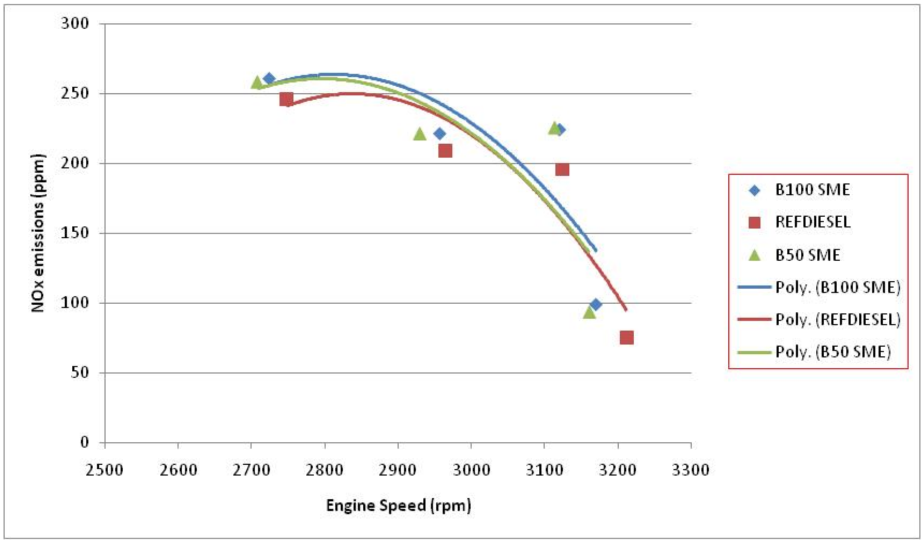

Figure 4. NO_x emissions using B50 SME, B100 SME and farm diesel.

Carbon monoxide concentrations decreased by 10% and 17% compared to diesel fuel when B20 SME and B100 SME were used, respectively. However, an average of 15% increase in CO concentrations was observed for B5 SME. In general, CO concentrations tended to decrease as the percentage of biodiesel in the fuel blend increases. These results are in agreement with Schumacher et al. (2001), who found that CO emissions decreased as biodiesel percentage in fuel blends increased.

At peak power, CO_2 emissions increased as the percentage of soy bean oil biodiesel increased. However, there was no definitive trend found with regards to the other speeds. Sulfur dioxide (SO_2) emissions results were similar for all test fuels, at any engine speed, with readings of less than 10ppm.

Conclusion

The performance and exhaust emissions of biodiesel fuels derived from soybean oil and Standard no. 2 ultra low-sulfur diesel fuel, using a 3-cylinder YANMAR diesel engine were evaluated. Based on the results of the experiments performed, the peak power produced using different blends of Soy bean oil biodiesel has no significant difference compared to that of the petroleum diesel. However, the brake-specific fuel consumption tends to increase as the percentage of biodiesel in a blend increases. Such an increase can be best described by the B50 SME and B100 SME test fuels.

Furthermore, the relationship between pollutant concentrations in diesel engine exhaust and the percentage of soy bean oil biodiesel in fuel blends was also determined. There was a significant reduction in the emissions of pollutant concentrations (i.e. NO_x and CO) as the percentage of biodiesel in a blend increased.

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