ENGINE PERFORMANCE AND EXHAUST EMISSIONS OF COTTONSEED OIL BIODIESEL

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Abstract

The objective of this research was to determine the relationship between engine performance and emissions of cottonseed oil biodiesel used in a 14.2 kW diesel engine. When using cottonseed oil biodiesel blends, CO, total hydrocarbon (THC), NO_x, and SO_2 emissions decreased as compared to petroleum diesel. Carbon dioxide emissions had no definitive trend in relation to cottonseed oil biodiesel blends. Carbon monoxide emissions increased by an average 15% using B5 and by an average of 19% using B100. Hydrocarbon emissions decreased by 14% using B5 and by 26% using B100. Nitrogen oxide emissions decreased by four percent with B5, five percent with B20, and 14% with B100. Sulfur dioxide emissions decreased by an average of 86% using B100, and by 94% using B50 blended with ultra-low sulfur diesel. The difference between peak output power when using biodiesel and when using diesel was insignificant in blends less than B40. Peak brake power when using B100 was about five percent lower than for diesel fuel. Pure cottonseed oil biodiesel achieved and maintained a peak corrected brake power of 13.1 kW at speeds of 2990, 2875, and 2800 rpm at loads of 41.3, 42.7, and 43.8 N-m. Using B5 produced a peak power of 13.6 kW at 2990 rpm and 43.9 N-m and at 2800 rpm and 46.7 N-m, while using B20 produced a peak power of 13.4 kW at 2990 rpm and 43.7 N-m. Brake-specific fuel consumption at peak load and torque when using B100 was 1238 g/kW-h. Brake-specific fuel consumption at peak power and loads using B5 and B20 were 1276 and 1155 g/kW-h.

Introduction

With the increased emphasis on the need for clean, renewable fuels, it is imperative to fully understand the operational characteristics of biodiesel. For many years, petroleum has been the primary source for diesel fuels (Schumacher et al., 2001). However, in recent years the supply of petroleum has slowed, while the need for petroleum fuels has substantially increased. According to the Environmental Protection Agency, or EPA, (2004), non-road diesel engines are significant contributors of air pollution in the United States. The primary pollutants of interest include carbon monoxide (CO), particulate matter (PM), nitrogen oxides (NO_x), and sulfur oxides (SO_x). The EPA has adopted new emissions standards for non-road diesel engines and sulfur reductions in non-road diesel fuel, effective August 30, 2004.

Sulfur in diesel fuel acts as an engine lubricant. If sulfur is removed from the diesel fuel, it will reduce fuel lubricity. While newer engines may be designed to handle low sulfur fuel, older engines may not. For example, fueling an older model engine with low sulfur diesel for an extended period of time may result in injectors sticking. Biodiesel is one solution to the removal of sulfur in diesel fuel due to its lubricating ability. Biodiesel is a cleaner-burning, renewable fuel that is compatible with petroleum diesel and can be produced domestically (NBB, 2006). While there is a wealth of available data regarding some types of biodiesel (Munoz et al., 2004), there is little data regarding the effect of cottonseed oil (CSO) biodiesel on diesel engine performance and exhaust emissions. According to the National Cottonseed Production Association, or NCPA, (2002) cottonseed oil ranks third in volume of oil produced in the United States behind soybean and corn oil. Recent trends have shown a decrease in desire to use CSO as food oil, since CSO contains trans-fatty acids. This trend has an inverse effect on the desire and availability of CSO to be used in biodiesel production. With the large amount of cotton produced in the southern United States, and the growing need for utilizing agricultural byproducts, it is important to investigate engine performance using biodiesel from cottonseed oil, as well as analyzing the exhaust emissions produced.

Objectives

The objective of this research is to gain a better understanding of cottonseed oil biodiesel by:

- Determining the relationship between diesel engine performance and the percentage of cottonseed oil biodiesel in fuel blends;

- Determining the relationship between pollutant concentrations in diesel engine exhaust and the percentage of cottonseed oil biodiesel in fuel blends; and
- Evaluating the implications of the results of this study with current and proposed regulations on the use of biodiesel and biodiesel blends as fuel for diesel engines.

Methods

Engine power tests were conducted using a 14.2 kW (19 hp) diesel engine fueled with several blends of petroleum diesel and cottonseed oil biodiesel. The CSO biodiesel used for all performance tests was purchased from Safe Renewable Fuels, Inc (Conroe, Texas). The blends included in these tests are enumerated as follows: B5/DF500; B20/DF500; B40/DF500; B60/DF500; B80/DF500; B100; and DF500.

Engine power tests were conducted using the SAE Standard Engine Power Test Code for diesel engines (SAE J-1349, 1983). Using the determined engine power and observed fuel consumption, brake-specific fuel consumption, or BSFC, can be calculated. Brake-specific fuel consumption is a useful indicator of the performance of fuels in engines, since it describes fuel consumption in relation to power produced. Determining the relationship between biodiesel blends and engine performance provides an understanding of the expected fuel consumption when using cottonseed oil biodiesel as fuel in a non-road diesel engine. Using this data, consumers can determine the cost effectiveness of using CSO biodiesel blends.

The engine was loaded for testing with a water-cooled eddy current absorption dynamometer rated at 22.4 kW (30 hp), manufactured by Pohl Associates, Inc., Hatfield, PA. Dynamometer load was controlled using a Dynamatic® EC 2000 controller (Drive Source International, Inc., Sturtevant, WI.). Torque and engine speed data were collected using LabView 8.0. Fuel flow was measured using a Model 214 Piston Flow Meter and transmitted using a Model 294 High Resolution, Linearized Frequency Transmitter (Max Machinery, Inc., Healdsburg, CA) Figure 1 shows the dynamometer test system.

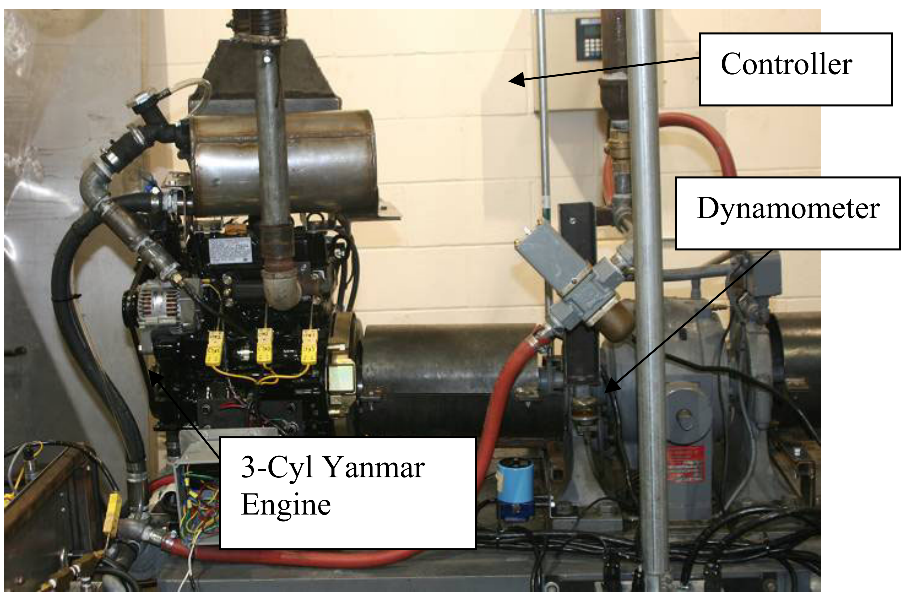

Figure 1. Dynamometer test system.

Performance tests were completed using three randomized blocks, with each block containing one set of tests for each fuel blend. Brake specific fuel consumption for each fuel blend at each speed interval was compared BSFC for DF500 using a t-test with a confidence interval of 0.95. These tests were used to determine whether or not there is significant difference between the BSFC of CSO biodiesel blends and DF500. Emissions tests were conducted concurrently with performance tests. Details of power, torque and specific fuel consumption calculations including all exhaust emissions data may be found in an M.S. Thesis by Powell (2007).

Results

Engine Performance Testing

Figure 2 shows brake power and torque for diesel and B100.

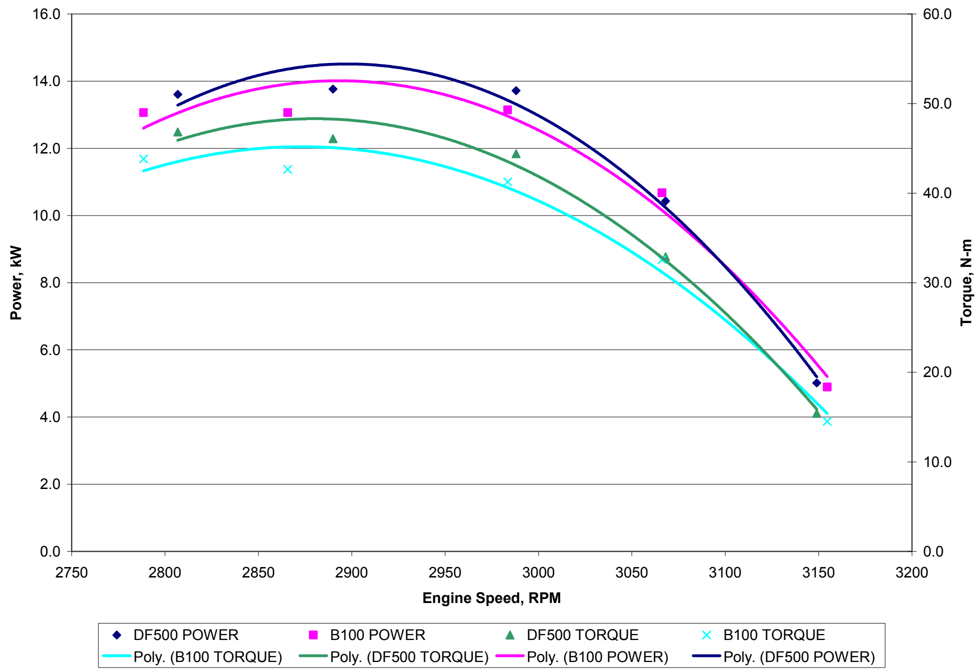

Figure 2. Brake Power and Torque using B100 and diesel.

The engine achieved a peak corrected brake power of 13.8 kW (18.5 hp) using farm diesel at an engine speed of approximately 2875 rpm. The peak power achieved when using B100, 13.1 kW (17.6 hp) was about five percent lower than when using diesel fuel. At high speeds (3065 rpm and greater), CSO biodiesel achieved approximately the same torque and brake power as diesel.

There is no significant difference in the engine performance when fueled with B5 and diesel. Peak brake power when using B5 was about one percent lower than when using pure diesel, and about four percent higher than when using B100. When using B5, the engine produced as much or more power than when using DF500 at speeds of 3150, 3065, and 2800 rpm.

Power achieved by each CSO biodiesel blend at a specific engine speed was compared to the power achieved by DF500 at the same engine speed. Only two scenarios produced significantly less power at a particular load: B100 at 2990 rpm and B20 at 2875 rpm. The significance in the difference in power produced when using B20 at 2875 rpm may be attributed to engine speed and load becoming unstable. The peak corrected brake power produced tended to decrease as the percent of CSO biodiesel in the fuel blend increased, but the decrease was usually insignificant. This is reasonable, since the energy content of biodiesel is lower than the energy content of farm diesel.

The brake-specific fuel consumption for diesel is lower than B100 at all speed. At each speed interval, BSFC tended to increase as the percentage of biodiesel in the blend increased. The BSFC for B100 was, on average, 19% higher than the corrected BSFC for DF500. When using B5, the corrected BSFC was eight percent higher than when using DF500, on average. The average corrected BSFC when using B20 was four percent lower than when using diesel fuel. This was the only blend that produced an average decrease in corrected BSFC when compared to diesel.

Corrected values for BSFC were found to be significantly different from that of DF500 when using B100 at 2990 rpm and when using B80 at 2875 rpm. .

In summary, the difference between peak output power when using biodiesel and when using diesel was insignificant in blends less than B40. Peak brake power when using B100 was about five percent lower than for diesel fuel. Pure cottonseed oil biodiesel achieved and maintained a peak corrected brake power of 13.1 kW at speeds of 2990, 2875, and 2800 rpm at loads of 41.3, 42.7, and 43.8 N-m. Using B5 produced a peak power of 13.6 kW at 2990 rpm and 43.9 N-m and at 2800 rpm and 46.7 N-m, while using B20 produced a peak power of 13.4 kW at 2990 rpm and 43.7 N-m. Brake-specific fuel consumption at peak load and torque when using B100 was 1238 g/kW-h. Brake-specific fuel consumption at peak power and loads using B5 and B20 were 1276 and 1155 g/kW-h.

Emissions Testing

Carbon monoxide concentrations decreased by 12 and 19% when using B20 and B100, respectively, when compared to diesel fuel. However, CO concentrations increased by an average of 15% when using B5. In general, CO concentrations tended to decrease as the percentage of CSO biodiesel in the fuel blend increases. The decrease is generally significant in blends of B60 and greater. These results are in agreement with Schumacher et al. (2001b), who found that CO emissions decreased as biodiesel percentage in fuel blends increased.

The results for the first set of tests for CO_2 show that, at 3150 rpm, CO_2 emissions increased as the percentage of CSO biodiesel increased; no definitive trend was found at other speeds. As expected, hydrocarbon emissions tended to decrease as the percentage of CSO biodiesel in the fuel blends increased. This decrease was significant in blends 80 percent or greater at speeds of 3065 rpm and 3150 rpm. When using B20, THC concentrations decreased by 14% when compared to DF500, while using B100 resulted in a 26% decrease. These results were similar to those observed by Krahl et al. (2005), who found that THC was significantly decreased when using biodiesel.

Figure 3 displays NO_x emissions obtained during the first set of tests.

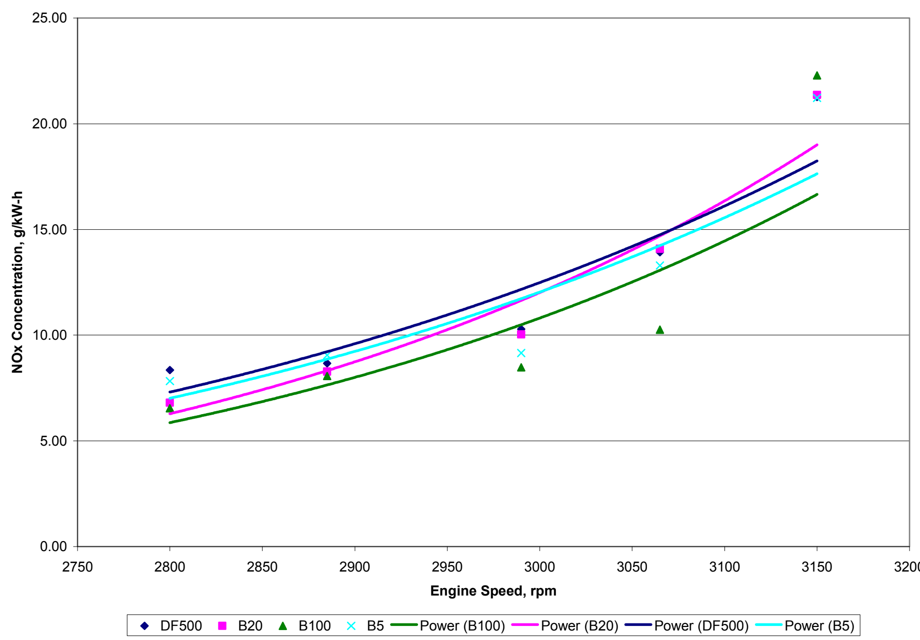

Figure 3. NO_x emissions using diesel, B5, B20, and B100.

On average, NO_x emissions decreased by four percent when using B5, and by five percent when using B20 as compared to diesel. When using B100, NO_x emissions decreased by 14%. Many of the previous emissions tests, such as those conducted by Graboski and McCormick (1998), were performed using soybean oil, which has an unsaturated to saturated fatty acid ratio of 5.7. Cottonseed oil has an unsaturated to saturated fatty acid ratio of 2.8. This difference in unsaturated fatty acid composition could factor into the decrease in NO_x emissions when using CSO B100.

Figure 4 below displays sulfur dioxide emissions obtained during the first set of tests when using diesel, B5. B20, and B100.

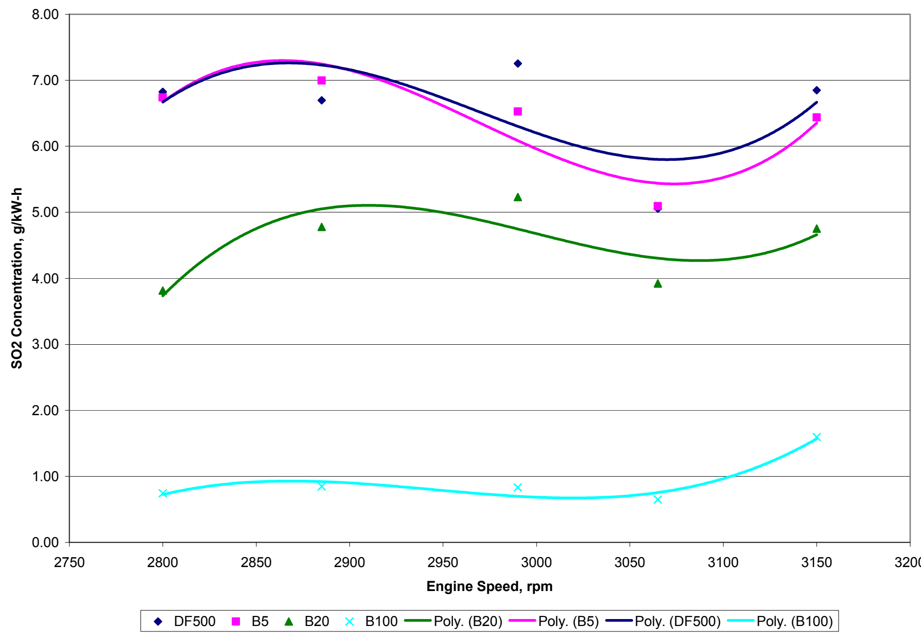

Figure 4. SO_2 emissions using diesel, B5, B20, and B100.

Sulfur dioxide emissions decreased as the percentage of CSO biodiesel in the fuel blends increased. The decrease in SO_2 emissions was consistently significant in CSO biodiesel blends of B20 and greater. The decrease in SO_2 concentrations ranged from two percent when using B5 to 86% when using B100. Given the decrease in fuel sulfur concentration, the decrease in SO_2 emissions was expected.

In summary, when using cottonseed oil biodiesel blends, CO, total hydrocarbon (THC), NO_x, and SO_2 emissions decreased as compared to petroleum diesel. Carbon dioxide emissions had no definitive trend in relation to cottonseed oil biodiesel blends. Carbon monoxide emissions increased by an average 15% using B5 and by an average of 19% using B100. Hydrocarbon emissions decreased by 14% using B5 and by 26% using B100. Nitrogen oxide emissions decreased by four percent with B5, five percent with B20, and 14% with B100. Sulfur dioxide emissions decreased by an average of 86% using B100, and by 94% using B50 blended with ultra-low sulfur diesel.

Conclusions

Peak power produced when using cottonseed oil biodiesel blends failed to match the peak power produced when using farm diesel. The peak power produced when using B100 was about five percent less than when using DF500. This difference is less than the difference in heating value between CSO biodiesel and diesel fuel (seven percent). The difference in peak power was not usually significant, especially when using biodiesel blends of less than B40. Likewise, the brake-specific fuel consumption tended to increase when using biodiesel blends, especially in blends with a high percentage of biodiesel, such as B80 and B100. The increase in corrected BSFC when using B100 ranged from nine percent at 2800 rpm to 34% at 3150 rpm. These results agree with Lin et al. (2006) and Cetinkaya et al. (2005), who observed a moderate decrease in output power when using biodiesel blends, and with Canakci and Van Gerpen (2001) who observed an increase in BSFC when using biodiesel blends.

The data presented in this section provides support for using biodiesel as a supplemental fuel for non-road diesel engines. When using small percentage fuel blends, such as B5 and B20, peak power and BSFC are not significantly different from that of straight farm diesel. This is in general agreement with Shaheed and Swain (1999), who observed no significant differences when using CSO biodiesel in a single cylinder 2.75 kW engine. Consumers that elect to use these blends can also take advantage of the lubricity of biodiesel. By producing and using cottonseed oil biodiesel as a fuel supplement, the agricultural industry is provided an opportunity to utilize an agricultural byproduct, as well as acting as an agent in the push toward becoming less dependent on non-renewable energy sources

Exhaust pollutant concentrations were compared using a t-test with a confidence interval of 0.95. These tests were used to determine whether or not there was a significant difference between exhaust pollutant concentrations measured when using biodiesel blends and when using DF500.

During the second set of tests, exclusive from performance tests, exhaust emissions were measured for each fuel blend at three pre-determined engine loads. For each fuel blend, the engine was started and allowed to warm up at half-throttle and an engine load of approximately 10.8 N-m (eight ft-lb). After a few minutes, throttle was increased until the engine reached WOT. Engine load was then increased to about 16.3 N-m (12 ft-lb), and the engine was allowed to run until engine speed and torque measurements were stabilized for two minutes. Once the measurements had stabilized, exhaust emissions measurements were collected. Once measurements were taken, the engine load was increased to approximately 32.5 N-m (24 ft-lb), and then to about 40.7 N-m (30 ft-lb) for exhaust emissions measurements. The concentrations measured were averaged using a simple arithmetic mean in order to provide a representative set of measurements for each blend at each load. Similarly to the performance tests, the engine was loaded for testing with a water-cooled eddy current absorption dynamometer rated at 30 hp, manufactured by Pohl Associates, Inc., Hatfield, PA. Dynamometer load was controlled using a Dynamatic® EC 2000 controller (Drive Source International, Inc., Sturtevant, WI.). Engine speed and torque data were collected using LabView 8.0. This second method of testing compared CSO biodiesel from two sources, as mentioned previously.

Carbon monoxide emissions tended to decrease as the percentage of CSO biodiesel increased. The EPA standards for CO emissions from a stationary and mobile non-road diesel engine were exceeded when using a CSO biodiesel blend of B5 at an engine speed of approximately 2875 rpm. The CO emissions standards were not exceeded with any other fuel blend at any other speed.

Total hydrocarbon emissions decreased as the percentage of CSO biodiesel increased. The decrease in THC concentrations was generally significant in blends of B60 and greater. Hydrocarbon concentrations decreased by 26% when using B100 as compared to DF500.

On average, NOx emissions decreased when using blends of B5, B20, B60, B80, and B100 when compared to DF500. On average, NO_x emissions were equal when using B40. EPA standards for NO_x emissions alone are not applicable for diesel engines rated between eight and 19 kW. However, the standard for NMHC +NO_x was consistently exceeded when using biodiesel blends, pure biodiesel, and farm diesel.

Sulfur dioxide concentrations decreased as the percentage of CSO biodiesel increased. This decrease tended to be significant in blends greater than five percent. The decrease in SO_s emissions was especially noticeable with ultra-low sulfur diesel (DF15). During the first tests, SO_2 emissions were decreased by an average of 86% when using B100; when using B50/DF15 during the second tests, SO_2 emissions were decreased by 96% at medium and high loads. These results are reasonable, considering the decrease in fuel sulfur content when blending diesel fuel with CSO biodiesel.

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