



EXPERIMENTAL STUDY OF COMBUSTION OF SOYBEAN OIL IN A DIESEL ENGINE

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Abstract: The use of vegetable oil methyl esters has been proposed as an alternative fuel for diesel engines. The purpose of this study is to investigate the combustion of soybean oil methyl ester in a direct injection diesel engine, and compare it to that of a conventional diesel fuel. Experimental measurements of performance, emissions, and rate of heat release were performed as a function of engine load for different fuel injection timings, and injector orifice diameters. It was found that overall, the soybean oil methyl ester behaved comparably to diesel fuel in terms of performance and rate of heat release. The methyl ester fuel gave lower HC emissions and smoke number than diesel fuel at optimum operating conditions. The results for CO emissions were varied. NO_x emissions were strongly related to the cylinder pressure development. This paper presents a brief history of diesel engine technology and an overview of soybean oil, including performance characteristics, economics, and potential demand. The performance and economics of soybean oil are compared with those of petroleum diesel.

Keywords: *Alternative fuel, lower HC emissions, smoke number, injection timing.*

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I. INTRODUCTION:

The idea of using vegetable oil for fuel has been around as long as the diesel engine. **Rudolph Diesel**, the inventor of the engine that bears his name, experimented with fuels ranging from powdered coal to peanut oil. In the early 20th century, however, diesel engines were adapted to burn petroleum distillate, which was cheap and plentiful. In the late 20th century, however, the cost of petroleum distillate rose, and by the late 1970s there was renewed interest in biodiesel. The most common sources of oil for biodiesel production in the United States are soybean oil and yellow grease (primarily, recycled cooking oil from restaurants). Blends of biodiesel and petroleum diesel are designated with the letter "B," followed by the volumetric percentage of biodiesel in the blend: B20, the blend most often evaluated, contains 20 percent biodiesel and 80 percent petroleum diesel; B100 is pure biodiesel. By several important measures biodiesel blends perform better than petroleum diesel, but its relatively high production costs and the limited availability of some of the raw materials used in its production continue to limit its commercial application.

Since the first oil crises of the 1970's alternative fuels have been investigated with the goal of replacing conventional petroleum supplies. The initial interest was mainly one of fuel supply but recently more attention has been focused on the use of renewable fuels in order to reduce the net production of CO₂ from combustion sources. Methanol and ethanol are two accepted alternative fuels which possess the potential to be produced from biomass sources. Neither of these fuels is well suited for use in diesel engines, and the use of high compression ratios, ignition improvers and ignition assistance devices is common.

One type of fuel which is well suited for use in diesel engines is that of vegetable oil based fuels. Previous studies have shown that it is possible to use vegetable oils in combination with alcohols in diesel engines with acceptable performance. Initial studies by **Barsic** and **Humke** showed that untreated vegetable oils can be used as fuels in diesel engines, but that there are severe problems with injector fouling. Lubricating oil effects with vegetable oil based fuels have also been studied. Experiments have shown that as far as combustion is concerned, one of the best ways to utilize alcohol in a diesel fuel is to combine it with a vegetable oil to make the corresponding ester of the vegetable oil. The most commonly used ester is the methyl ester, made by combining the vegetable oil with methanol. In fact,



in some parts of Europe, rape seed methyl ester is already commercially available for use in vehicles.

II. HISTORY:

The efficiency of the Carnot cycle increases with the increase in compression ratio—the ratio of gas volume at full expansion to its volume at full compression. This concept gave a motivation to **Rudolph Diesel** to build an engine with the highest possible compression ratio. He introduced fuel only when combustion was desired and allowed the fuel to ignite on its own in the hot compressed air. Diesel's engine achieved efficiency higher than that of the Otto engine and much higher than that of the steam engine.

Diesel received a patent in 1893 and demonstrated a workable engine in 1897. Today, diesel engines are classified as “compression-ignition” engines. Diesel's motivation was not only to improve efficiency but also to bring the benefits of powered machinery to smaller companies. Steam engines were so large that only the biggest firms could afford them, and Diesel wanted to enable smaller firms to compete against larger, steam-powered firms. He used peanut oil as the fuel for his demonstration engines at the 1900 World's Fair and thought that oils from locally grown crops would be used to power his engines. The early 20th century saw the introduction of gasoline- powered automobiles. Oil companies were obliged to refine so much crude oil to supply gasoline that they were left with a surplus of distillate, which is an excellent fuel for diesel engines and much less expensive than vegetable oils.

On the other hand, resource depletion has always been a concern with regard to petroleum, and farmers have always sought new markets for their products. Consequently, work has continued on the use of vegetable oils as fuel. Early durability tests indicated that engines would fail prematurely when operating on fuel blends containing vegetable oil. Engines burning vegetable oil that had been transesterified with alcohols, however, exhibited no such problems and even performed better by some measures than engines using petroleum diesel. The formulation of what is now called biodiesel came out of those early experiments.

The term “biodiesel” means the monoalkyl esters of long chain fatty acids derived from plant or animal matter which meet (A) the registration requirements for fuels and fuel additives established by the Environmental Protection Agency under section 211 of the



Clean Air Act (42 U.S.C. 7545), and (B) the requirements of the American Society of Testing and Materials D6751.

Bus running on soybean biodiesel. Photo: U.S. Department of Energy



That definition of biodiesel is used here, although other processes also can be used to produce high-quality diesel fuel from vegetable oil or animal fat.

III. PERFORMANCE AND EMISSIONS CHARACTERISTICS:

One of the most important characteristics of diesel fuel is its ability to auto ignite, a characteristic that is quantified by a fuel's cetane number or cetane index, where a higher cetane number or index means that the fuel ignites more quickly.⁷ U.S. petroleum diesel typically has a cetane index in the low 40s, and European diesel typically has a cetane index in the low 50s. Lubricity, another important characteristic of diesel fuel, is a measure of lubricating properties.

Fuel injectors and some types of fuel pumps rely on fuel for lubrication. One study, published in 1998 and cited by the National Biodiesel Board, found that one-half of samples of petroleum diesel sold in the United States did not meet the recommended minimum standard for lubricity. Biodiesel has better lubricity than current low-sulfur petroleum diesel, which contains 500 parts per million (ppm) sulfur by weight. The petroleum diesel lubricity problem is expected to get worse when ultra-low-sulfur petroleum diesel (15 ppm sulfur by weight) is introduced in 2006. A 1- or 2-percent volumetric blend of biodiesel in low-sulfur petroleum diesel improves lubricity substantially. It should be noted, however, that the use of other lubricity additives may achieve the same effect at lower cost. Biodiesel also has some performance disadvantages. The performance of biodiesel in cold conditions is



markedly worse than that of petroleum diesel, and biodiesel made from yellow grease is worse than soybean biodiesel in this regard. At low temperatures, diesel fuel forms wax crystals, which can clog fuel lines and filters in a vehicle's fuel system.

The "cloud point" is the temperature at which a sample of the fuel starts to appear cloudy, indicating that wax crystals have begun to form. At even lower temperatures, diesel fuel becomes a gel that cannot be pumped. The "pour point" is the temperature below which the fuel will not flow. The cloud and pour points for biodiesel are higher than those for petroleum diesel. Another disadvantage of biodiesel is that it tends to reduce fuel economy. Energy efficiency is the percentage of the fuel's thermal energy that is delivered as engine output, and biodiesel has shown no significant effect on the energy efficiency of any test engine. Volumetric efficiency, a measure that is more familiar to most vehicle users, usually is expressed as miles traveled per gallon of fuel (or kilometers per liter of fuel). The energy content per gallon of biodiesel is approximately 11 percent lower than that of petroleum diesel.¹⁴ Vehicles running on B20 are therefore expected to achieve 2.2 percent (20 percent x 11 percent) fewer miles per gallon of fuel. Since the possibility exists for the decomposition of the methyl ester during the ignition delay period, and the viscosity of the methyl is somewhat higher than that of typical diesel fuel, one might expect to observe some differences in the combustion behavior of methyl ester as compared to diesel fuel.

From previous experiments, the differences are not expected to be large, but the present study was undertaken to examine the combustion process in more detail than had been done previously. The goal of the study was to evaluate the effects of changes in the injection system on the combustion, performance and emissions of a direct injection diesel engine powered by soybean oil methyl ester.

IV. EXPERIMENTAL CONDITIONS:

The engine used for the study was a 4-cylinder, 4-Stroke, normally aspirated direct injection diesel engine. The engine and test condition specifications are given in Table 1.



Table 1. Specifications of the engine and test conditions

Bore	96.4 mm
Stroke	104.8 mm
Displacement	3.06 liter
Compression Ratio	16.5
Speed	1800 rpm
Intake Pressure	760 mm Hg
Exhaust Pressure	Atmospheric
Coolant Temperature	82 °C
Oil Temperature	71 °C

The injection system consisted of a standard rotary distributor pump with pencil type nozzles. The standard orifice diameter for the engine was 0.279 mm. Tests were also conducted with an orifice diameter of 0.229 mm. Injecting timing was changed by rotation of the pump with respect to the camshaft. The fuels used in the study were standard number 2 diesel fuel as the reference fuel, and soybean oil methyl ester. The characteristics of the fuels are shown in Table 2. The cetane numbers of the fuels tested were not measured for this study. Previous work has indicated that the cetane number of the diesel fuel is expected to be about 51 and that of the methyl ester is expected to be about 46.

Table 2 Specifications of the test fuels

Bore	96.4 mm
Stroke	104.8 mm
Displacement	3.06 liter
Compression Ratio	16.5
Speed	1800 rpm
Intake Pressure	760 mm Hg
Exhaust Pressure	Atmospheric
Coolant Temperature	82 °C
Oil Temperature	71 °C

V. TESTING PROCEDURES:

The engine was instrumented and engine exhaust emissions testing equipment were calibrated. Engine performance was checked at peak power and peak torque to ensure proper operation. The two-point check was performed throughout the project to maintain a record of engine performance. The pre-mixed drum of blended fuel was connected to the fuel supply system of the engine. The engine was idled while the return fuel line from the



engine drained. The fuel system was purged before the return fuel was redirected to the recirculation tank. Purged fuel was placed in a waste fuel tank. The engine was operated at 1200 and 2100 rpm at 50% and 100% load for ten minutes. A two point power check was run. The engine was accelerated to rated power (2100 rpm full throttle) and held there until engine oil temperature stabilized (230 to 240oF). Exhaust backpressure was checked and then three logs of measured engine parameters were recorded. The engine was then decelerated to peak torque speed (1200 rpm full throttle). Engine exhaust backpressure and three measures of engine operating parameters were recorded.

VI. ENGINE PERFORMANCE:

The following observations were based on the data collected during this investigation:

- Peak torque was not affected by the addition of up to 40% biodiesel; however, a slight drop at rated speed was noticed at the 40% level.
- A steady drop in exhaust gas temperature was observed for both the rated and peak torque condition, indicating a shift in the peak pressure point toward top dead center, resulting from an increasingly shorter ignition delay. The lower exhaust gas temperature was a result of increased heat transfer into the coolant.
- The reduced ignition delay and increased peak pressure and temperature contributed to the increased oxides of nitrogen. This was most pronounced at peak torque, which generated the highest peak pressures and temperatures.
- Fuel consumption on a mass basis was very similar for all blends tested.

VII. EMISSIONS:

Emissions results follow trends established by previous research. Increased levels of biodiesel increase NO_x while reducing PM. Proportionally, PM reduction was slightly more than the increase in NO_x, on a percentage basis. The decrease in PM was contributed to the oxygen in the fuel. The reduction in CO and THC was linear with the addition of biodiesel for the blends tested. These reductions indicate more complete combustion of the fuel. The presence of oxygen in the fuel was thought to promote complete combustion. The BSFC and CO₂ did not change appreciably, and fuel consumption increased only minimally over the test cycle. The 20% blend represented a good compromise between increased NO_x and reduction of all other emissions. This biodiesel/diesel fuel blend was recommended.



VIII. RECOMMENDATIONS:

The Environmental Protection agency has mandated that the level of oxides of nitrogen emissions be equal to or less than the emissions produced by the engine if fueled on reference diesel fuel. Economic conditions concerning the use of biodiesel as a transportation fuel dictate that the fuel should be used as a blend in a diesel engine. As such the following recommendations were made:

- Engine optimization strategies should be developed that fully takes advantage of the physical and chemical makeup of biodiesel.
- Additional tests should be conducted to evaluate other catalytic converters, and the durability of these devices should be documented over time.

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