Comparative Performance, Emission, and Combustion Characteristics of Rice-Bran Oil and Its Biodiesel in a Transportation Diesel Engine

Article *in* Journal of Engineering for Gas Turbines and Power · June 2010

DOI: 10.1115/1.4000143

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Comparative Performance, Emission, and Combustion Characteristics of Rice-Bran Oil and Its Biodiesel in a Transportation Diesel Engine

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The methyl esters of vegetable oils known as biodiesel are becoming increasingly popular because of their low environmental impact and potential as a green alternative fuel for diesel engines. Methyl ester of rice-bran oil (RBOME) is prepared through the process of transesterification. In the present investigation, experiments have been carried out to examine the performance, emission, and combustion characteristics of a direct-injection transportation diesel engine running with diesel, 20% blend of rice-bran oil (RBO), and 20% blend of RBOME with mineral diesel. A four-stroke, four-cylinder, direct-injection transportation diesel engine (MDI 3000) was instrumented for the measurement of the engine performance, emissions, in-cylinder pressure-crank angle history, rate of pressure rise, and other important combustion parameters such as instantaneous heat release rate, cumulative heat release rate, mass fraction burned, etc. A careful analysis of the performance, emissions, combustion, and heat release parameters has been carried out. HC, CO, and smoke emissions for RBO and RBOME blends were lower than mineral diesel while NO_x emissions were almost similar and brake specific fuel consumption (BSFC) was slightly higher than mineral diesel. Combustion characteristics were quite similar for the three fuels.
[DOI: 10.1115/1.4000143]

Keywords: biodiesel, rice-bran oil, combustion, pressure-crank angle diagram, heat release analysis, emissions

1 Introduction

Depletion of petroleum reserves, rising vehicle population, increasing fuel prices, and uncertainties concerning petroleum availability, stringent emission standards, and global warming due to carbon dioxide emissions, have forced the development of alternate energy sources, which are becoming increasingly important. Vegetable oils have comparable energy density and cetane number as that of mineral diesel [1]. Physical and chemical characteristics of the vegetable oil can be improved by transesterification process, leading to reduction in fuel viscosity, which would otherwise cause problems in fuel injection and may cause nozzle wear [2–4]. The resultant product, i.e., biodiesel, has higher cetane number and heating value closer to mineral diesel. Also, carbon cycle time for fixation of CO_2 from biodiesel is quite small compared with mineral diesel. This means that biodiesel usage will effectively reduce greenhouse gas emissions [5].

Some researchers reported improved engine performance, particularly thermal efficiency for biodiesel fuelled engines [2–4,6–17]. With the use of biodiesel as a fuel in the engine, there is considerable reduction in harmful emissions like CO, HC, and smoke, but NO_x emissions increase [2–4,6–16]. Most of the western countries use edible oils such as soybean, sunflower, saffola, etc., for the production of biodiesel. In South Asia, variety of nonedible oils like linseed, mahua, karanja, rice-bran, and jatropha are available in abundance, which can be utilized for the production of biodiesel. Some of these oils have already been evaluated as substitute diesel fuels [2,3,6,8,18]. Agarwal and Das [2] used linseed oil methyl ester as a fuel in stationary engines. They found that 20% blend of linseed oil methyl ester was optimum blend, and it gave maximum benefit in terms of thermal efficiency. Similar results were found in our earlier study for rice-bran oil on a transportation diesel engine [3]. This study showed improved performance of the engine with reduction in the exhaust emissions except NO_x [3]. Zhang and Van Gerpan [13] investigated the combustion characteristics of turbocharged direct-injection diesel engine using blends of methyl, isopropyl, and winterized methyl ester of soybean oil with diesel as fuel. They found that all fuel blends except isopropyl ester had similar combustion behavior. Ignition delay for ester/diesel blend was shorter than mineral diesel as a fuel. Senatore et al. [14] showed that with rapeseed oil methyl ester, heat release is advanced as compared with diesel. Also injection starts earlier in the case of biodiesel as a fuel and average cylinder gas temperature was higher for biodiesel. Senthil Kumar et al. [18] found that for jatropha oil methyl ester, ignition delay was higher as compared with ignition delay for diesel in a constant speed diesel engine. Selim et al. [4] tested jojoba oil methyl ester (JME) as a fuel on Ricardo compression swirl diesel engine and found that the pressures and pressure rise rates for JME are almost similar to those of gas oil. JME, however, exhibits slightly lower pressure rise rate than gas oil, and esters seem to have slightly delayed combustion.

Blending of vegetable oils in small concentration ($<20\%$) with diesel is found to reduce the viscosity to acceptable American Society of Testing and Materials (ASTM) limits. Various governments in their transport/biodiesel policy have targeted to replace about 20–30% petroleum based fuels with biofuels due to availability issues (e.g., European Union (EU) 10% petrol and diesel from renewable sources until 2020; India has targeted 20% biodiesel and ethanol content until 2017, etc.). In this scenario, many sources of biodiesel need to be utilized simultaneously and rice-bran oil is one of the major surplus oil available for this purpose. It was realized that very little information is available on the performance, emission, and combustion behavior of rice-bran oil and rice-bran oil ester blends. The objective of this study is to critically evaluate and compare the performance of 20% blend of rice-bran oil methyl ester (RBOME20) and 20% blend of rice-bran oil (RBO20), vis-à-vis, mineral diesel.

2 Fuel Preparation and Characterization

Rice-bran oil was transesterified using methanol in the presence of an alkaline catalyst (NaOH). Process parameters like temperature, catalyst amount, molar ratio of alcohol to oil, and reaction temperature were optimized and it is found that 9:1 molar ratio of alcohol to oil, 55°C temperature, 0.75% (w/w) catalyst, and 1 h reaction time is optimum for the transesterification of rice-bran oil [9]. Characterization of rice-bran oil, rice-bran oil methyl ester, and diesel were done in the laboratory as per the relevant ASTM norms. Some fuel properties are shown in Table 1.

3 Experimental Setup

A transportation direct injection (DI) diesel engine (MDI 3000, Mahindra & Mahindra Ltd., India) was used for conducting the engine experiments. The specifications of the engine are given in Table 2.

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Manuscript received April 30, 2009; final manuscript received May 14, 2009; published online March 24, 2010. Editor: Dilip R. Ballal.

Table 1 Properties of the fuels

Characteristics	Rice-bran oil (RBO)	Mineral diesel (D)	Rice-bran oil methyl ester (RBOME)	20% rice-bran oil blend (RBO20)	20% biodiesel blend (RBOME20)
Specific gravity at 30°C	0.928	0.839	0.877	0.887	0.847
Viscosity (cS) at 40°C	42	3.18	5.3	4.9	3.48
Calorific value (MJ/Kg)	40.3	44.8	42.2	43.9	44.3
Flash point (°C)	316	68	183	–	–
Fire point (°C)	337	103	194	–	–
C:H:O (%)	74:11:12	82:13:1	73:13:11.6	–	–

The engine was coupled with an eddy current dynamometer (ASE 70, Schenck Avery Ltd., India). A piezoelectric pressure transducer (GU21C, AVL, Austria) was installed in the engine cylinder head to measure the combustion pressure. Signals from the pressure transducer were given to the charge amplifier. A high-precision shaft encoder was used for delivering signals for top dead center (TDC) and the crank angle with a precision of 0.1 deg crank angle. The signals from the charge amplifier and shaft encoder were supplied to a high-speed data acquisition system (Indimeter-619, AVL, Graz, Austria).

Three fuels, namely, RBO20, RBOME20, and mineral diesel were tested at different engine load conditions at two speeds (1800 rpm and 2400 rpm). Cylinder pressure data were acquired for 50 consecutive cycles and then the average was taken for eliminating the effect of cycle-to-cycle variations. All tests were carried out under steady state engine operating conditions.

4 Performance and Emission Tests

Experiments were conducted using RBO20, RBOME20, and mineral diesel. BSFC was found to be highest for RBO20 followed by RBOME20 (Fig. 1) at 1800 rpm; however, at 2400 rpm, BSFC for RBOME20 is better than even mineral diesel. Brake thermal efficiency (BTE) is affected differently by the engine speed variation for different fuels. Thermal efficiency of mineral diesel is highest at 1800 rpm while at 2400 rpm it is highest for RBOME blend followed by mineral diesel. Oxygen present in biodiesel molecules leads to improved combustion of fuel, therefore resulting in lower emission formation. In the case of RBO, higher viscosity prevents adequate fuel atomization (due to relatively higher fuel viscosity), which leads to inferior combustion compared with mineral diesel. Calorific value of RBO is lowest followed by RBOME; therefore this trend of BSFC (Fig. 1) is expected. Exhaust gas temperatures for all the fuels are quite close at 1800 rpm (Fig. 2) but slightly higher for mineral diesel followed by RBO20 and RBOME20 at 2400 rpm. Since all other results at 2400 rpm are similar to that at 1800 rpm, the experimental results at 2400 rpm have not been shown/discussed in the interest of space. The smoke opacity was analyzed using smoke opacimeter (AVL437, AVL, Austria). Smoke opacity was highest for mineral diesel and lowest for RBOME20. Smoke opacity increases with increasing engine speed and increasing engine load (Fig. 2).

The emission tests were conducted on these fuels using raw exhaust gas emission analyzer (EXSA 1500, Horiba, Japan). All the observed raw emission values are converted into mass emissions. Lowest CO_2 emissions were observed for mineral diesel (Fig. 3) at 1800 rpm. CO_2 emissions for mineral diesel were quite close to RBOME20, however slightly higher for RBO20. NO_x emissions for mineral diesel and RBOME20 were almost comparable (Fig. 3). The emissions of CO slightly decrease both for RBO20 and RBOME20 at lower engine loads (Fig. 4); however, at higher engine load conditions, CO emissions for all the fuels

Table 2 Specifications of the engine

Type of engine	Four-stroke, naturally aspirated, water cooled engine
Number of cylinders	Four
Bore/stroke (mm)	88.9/101.6
Displacement volume (cc)	2520
Compression ratio	18:1
Rated power	40.4 kW at 3000 rpm
Maximum torque	152 N m at 1800 rpm
Injection system	In-line reciprocating mechanical pump
Injection timing	17 ± 1 deg BTDC
Injector opening pressure	$214-194$ kg/cm^2

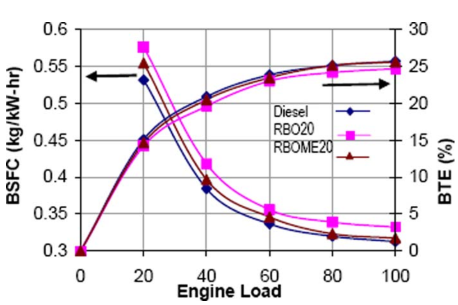

Fig. 1 BSFC and thermal efficiency at 1800 rpm

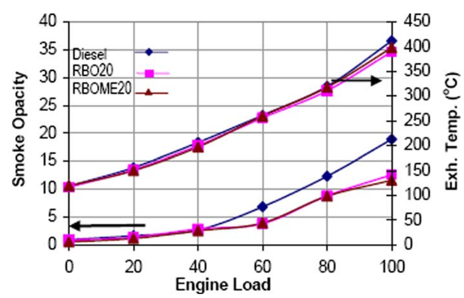

Fig. 2 Smoke opacity and exhaust temperature at 1800 rpm

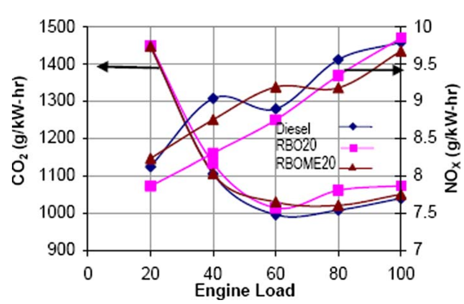

Fig. 3 CO_2 and NO_x emissions at 1800 rpm

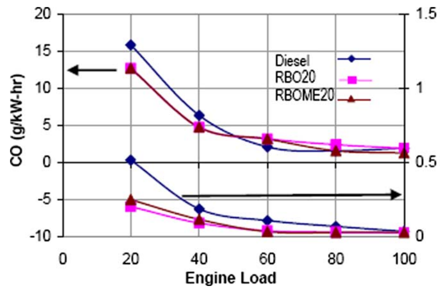

Fig. 4 CO and HC emissions at 1800 rpm

were approximately similar. HC emissions were highest for mineral diesel followed by RBOME20 and lowest for RBO20 (Fig. 4).

5 Combustion Analysis

In a compression ignition engine, cylinder pressure depends on the burned fuel fraction during the premixed combustion phase, i.e., initial stage of combustion. Cylinder pressure characterizes the ability of the fuel to mix well with air and burn. High peak pressure and maximum rate of pressure rise correspond to large amount of fuel burned in the premixed combustion stage. The cylinder pressure-crank angle history is obtained at different loads for mineral diesel, RBO20, and RBOME20. Peak pressure and maximum rate of pressure rise are obtained at different loads from these measurements.

Representative results of cylinder pressure and instantaneous rate of heat release at no load and full load at 1800 rpm are discussed in the following paragraphs (Figs. 5 and 6). At all engine loads, in-cylinder pressure curves for mineral diesel, RBOME20, and RBO20 are almost the same except that RBO20 shows slightly earlier start of combustion. As engine load increases, this difference in the start of combustion timing among the three fuels reduces. Earlier start of combustion for RBOME20 may be caused by shorter ignition delay (high cetane number), and for RBO20, it may be caused by advancing of fuel injection due to higher bulk modulus of the RBO20.

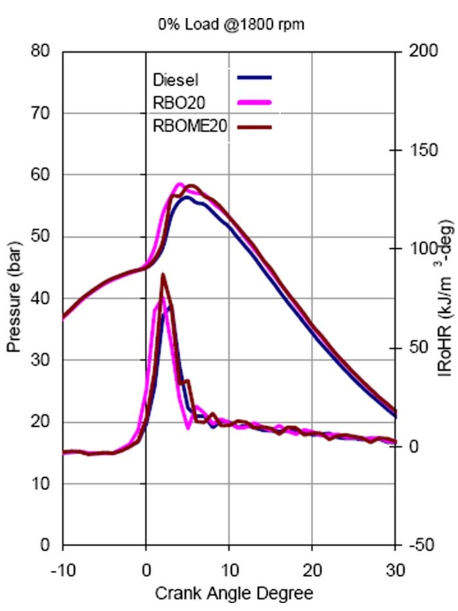

Fig. 5 Comparison of in-cylinder pressure and heat release rate variation at no load condition

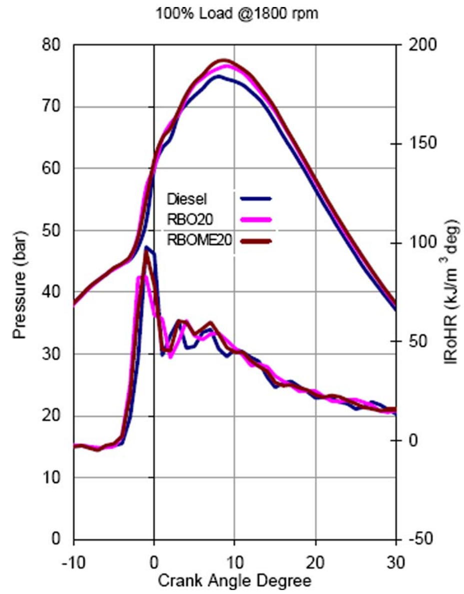

Fig. 6 Comparison of in-cylinder pressure and heat release rate variation at full load condition

Peak pressure for all the fuels occur between 4–8 deg crank angle after top dead center (ATDC) at 1800 rpm and 4–9 deg crank angle ATDC at 2400 rpm. Peak pressure is slightly higher for RBOME20 at 1800 rpm in all the engine loads. From the heat release diagram it is evident that the initial rate of heat release is slightly higher for mineral diesel in the beginning of the combustion. All fuels experience rapid premixed burning, followed by diffusion combustion as is typical of naturally aspirated diesel engines. After the ignition delay period, the premixed fuel-air mixture burns rapidly, releasing heat at a very rapid rate, after which diffusion combustion takes place, where the burning rate is controlled by the availability of combustible fuel-air mixture.

It can be noted that at no load condition, most of the heat releases take place in the premixed combustion phase, whereas at full load, significant amount of heat release also take place in the diffusion combustion phase. This diffusion combustion phase heat release is relatively higher for RBO20 and RBOME20 compared to mineral diesel.

Figure 7 shows the cumulative heat release curve for no load and full load conditions at 1800 rpm. Cumulative heat release is marginally higher for both RBO20 and RBOME20 at low load compared with mineral diesel (Fig. 7). At medium and high load the cumulative rate of heat release for RBO20 and RBOME20 are almost the same as with mineral diesel.

Mass burn rate of the fuel can be found out from the cumulative heat release diagram. Figure 8 shows the crank angle at which 10% and 90% mass of fuel is burned. This figure shows that 10%

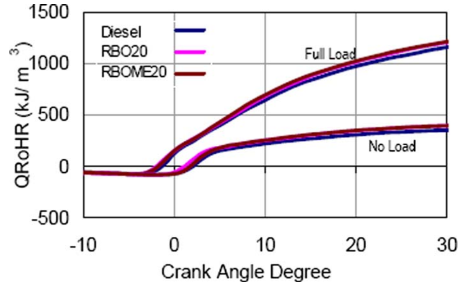

Fig. 7 Comparison of cumulative heat release rate variation at idle and full load conditions

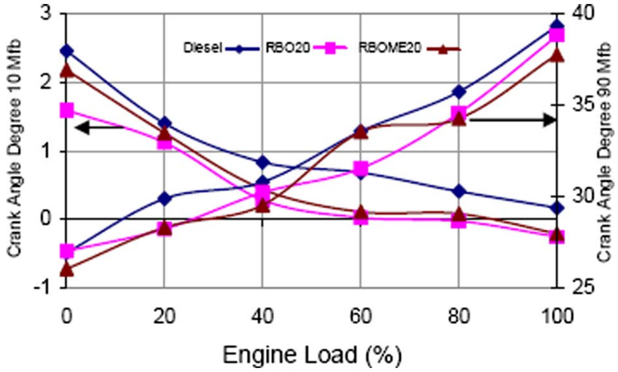

Fig. 8 Crank angle for 10% and 90% mass burns at 1800 rpm

of fuel burns earlier for the RBO20 and 90% of the fuel is burned earlier in case of RBOME20, showing faster burning of RBOME20 compared to mineral diesel and RBO20. Combustion duration for all the fuels increases as the load is increased due to the increase in the quantity of fuel injected. From all these diagrams and discussions, it is amply clear that RBO20 and RBOME20 have shorter ignition delay compared with mineral diesel; however, the burning speed of RBO20 is relatively slower.

6 Conclusions

A detailed experimental analysis for finding out the performance, emission, and combustion characteristics of RBO20 and RBOME20, vis-à-vis, mineral diesel was carried out. HC and CO emissions for both RBO20 and RBOME20 were lower than mineral diesel. NO_x emissions are comparable for all the three fuels at all load and speed conditions. BSFC for RBO20 was higher than mineral diesel but BSFC for RBOME20 was quite close to mineral diesel. Combustion of RBOME20 was found to be more efficient than mineral diesel but thermal efficiency of RBO20 was inferior to mineral diesel. CO_2 emissions for RBO20 were slightly higher than mineral diesel but almost similar for RBOME20 and mineral diesel. Smoke opacity for both RBO20 and RBOME20 was better than mineral diesel.

Various combustion parameters such as pressure-crank angle diagram, peak pressures, crank angle for peak pressure, crank angle for 10% mass burn, crank angle for 90% mass burn, instantaneous heat release rate, cumulative heat release, etc., were evaluated for different engine loads in the transportation diesel engine. The experimental investigations revealed that the overall combustion characteristics were quite similar for RBOME20, RBO20, and mineral diesel. For RBO20 and RBOME20, ignition delay is lower compared to mineral diesel. RBO20 and RBOME20 did not cause any fuel/combustion related problems. The ignition delay was shorter for RBO20 and RBOME20 compared with mineral diesel; however, the burning rate was relatively slower for RBO20. This detailed experimental investigation suggests that 20% blend of biodiesel as well as 20% rice-bran oil can substitute mineral diesel without any significant modification in medium duty transportation DI diesel engine.

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