

Performance and Emissions of a Diesel Engine Fueled by Biodiesel Derived from Different Vegetable Oils and the Characteristics of Combustion of Single Droplets

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ABSTRACT

This paper investigates the performance, combustion characteristics, and emissions of a small single cylinder DI diesel engine with biodiesel fuel (BDF) derived from unused rape, soybean, and palm oils. Compared with ordinary gas oil, the BDFs showed similar brake thermal efficiencies, better ignitability, and considerably reduced smoke densities, while the NO_x emissions were somewhat higher. The injection characteristics and engine performance were also examined using neat Methyl Oleate (OME) and OME-Methyl Palmitate (PME) blends. Basic experiments of suspended single droplets were performed to evaluate the differences in ignition, combustion, and soot formation characteristics of these fuels. The results showed shorter ignition lags and combustion durations for the OME droplets blended with PME and the soot formation rate with OME is about 13% that of gas oil droplets.

INTRODUCTION

Biodiesel fuel (BDF) is a transesterified vegetable oil using an alcohol, mainly methanol. The properties of biodiesel are close to those of gas oil and a number of studies have been conducted in diesel engines with BDFs as diesel fuel substitutes [1]-[21]. The BDF is renewable and sulfur free and offers potential reductions in carbon dioxide emissions, practical application to automobiles is increasing globally. As vegetable oil contains different kinds of fatty acids, this causes the formation of different components of fatty acid methyl ester (FAME) in the transesterification. Therefore, it is necessary to establish the influence of the FAME composition on the injection characteristics, spray

characteristics, engine performance, and combustion and emission characteristics.

The present study used three kinds of BDF derived from different feedstock, and chemical reagents, oleate methyl ester (OME) and palmitate methyl ester (PME) which are the major components of FAME in biodiesel fuel. Firstly, the performance and emissions of a small single cylinder DI diesel engine were evaluated using the three kinds of BDF derived from unused rape oil, soybean oil, and palm oil. Compared with ordinary gas oil, the results for all the BDFs showed similar brake thermal efficiencies and considerably reduced smoke densities while the NO_x emissions were somewhat higher. The BDF, especially that with palm oil BDF, showed better ignitability than with gas oil operation.

The rape oil BDF and palm oil BDF used in the tests are mainly composed of OME and PME. Therefore, the injection characteristics and engine performance of neat OME and OME-PME blends were examined. Here, it was found that the bulk modulus of OME was about 7 % higher than gas oil under low injection pressure conditions as in the tested engine here. To clarify the influence of FAME composition on combustion and emission characteristics, the engine was operated with neat OME and OME-PME blends. Compared with gas oil operation, the FAME fuels showed similar brake thermal efficiencies and somewhat higher NO_x emissions, while the smoke densities and THC emissions decreased significantly. The ignition characteristics were considerably improved when PME was blended with OME.

Table 1 Properties of the tested fuels

	Gas oil	Rape Oil BDF	Soybean Oil BDF	Palm Oil BDF	OME	PME
Density [15°C] (g/cm ³)	0.826	0.879 ^(*)	0.881 ^(*)	0.871 ^(*)	0.877	0.852
Viscosity [30°C] (mm ² /s)	3.0	5.9	5.4	5.8	6.3	—
Net calorific value (MJ/kg)	42.91	37.06	36.71	36.91	37.26	37.12
B.P. at 20 % distil. (°C)	243.0	354.5 ^(*)	352.5 ^(*)	333.5 ^(*)	214 (2kPa)	191(2kPa)
Carbon (mass %)	86.1	77.2	77.0	76.4	77.0	75.5
Hydrogen (mass %)	13.8	12.1	12.0	12.4	12.2	12.7
Oxygen (mass %)	—	10.8	11.0	11.1	10.8	11.8
Water (ppm)	—	457	821	425	—	—

^(*) at 20°C ^(*) measured by Gas Chromatography

Table 2 Fatty Acid Methyl Ester (FAME) compositions

	Composition C** : N ^(*)	Rape Oil BDF	Soy Oil BDF	Palm Oil BDF
Lauric acid M.E.	C12:0	—	—	0.4
Myristic acid M.E.	C14:0	—	0.4	1.1
Palmitic acid M.E.	C16:0	4.2	14.0	42.2
Stearic acid M.E.	C18:0	1.7	4.7	3.0
Oleic acid M.E.	C18:1	63.0	33.8	43.0
Linoleic acid M.E.	C18:2	19.7	42.4	10.3
Linolenic acid M.E.	C18:3	11.4	4.7	—

^(*) C**: Chain length of fatty acid, N: Number of double bonds

Basic experiments with suspended single droplets were performed to evaluate the differences in evaporation, ignition, and combustion characteristics of the FAME fuels. The experiments used an electric furnace maintained at high temperature (860°C) at atmospheric pressure. The quartz bar used to suspend the oil droplet has a spherical tip (0.6mm diameter), and the droplet was placed manually, quickly in the chamber. The results show ignition lags and combustion durations of neat OME droplets to be shorter when blended with PME. The experiments also evaluated the soot formed during the droplet combustion process. The soot was trapped on a glass fiber filter, and the mass of the filter was determined with a microbalance. The results showed that the soot formation rate (defined as the mass ratio of soot to droplet) with OME is about 13% of that of gas oil droplets.

A number of studies have been conducted to determine the influence of the biodiesel source compounds and fatty acid ester composition on engine performance, combustion characteristics, and emissions [9]-[14]. Reports worthy of special attention [9][11] deal with a series of fuels consisting of nearly pure fatty acid esters with different chain lengths and numbers of double bonds as well as a variety of feedstock: the effects of fuel characteristics, PM emissions, NOx emissions, and

other parameters including unregulated pollutants have here been described in detail. However, there are few reports of biodiesel droplet combustion [15][17], and the influence of FAME composition on the combustion and soot formation characteristics using FAME fuel droplets is not fully elucidated.

EXPERIMENTAL APPARATUS AND METHODS

FUEL – The study used three kinds of BDF (biodiesel fuel) derived from unused rape oil, soybean oil, and palm oil; two kinds of commercial FAME (fatty acid methyl ester) fuels: OME (methyl oleate, purity 70%) and PME (methyl palmitate, purity >95%); and gas oil for automobiles. The particulars of the tested fuels are shown in Table 1. Compared with gas oil, the density and kinematic viscosity of the BDF and FAME fuels are higher while the net calorific value is about 14% lower than that of gas oil. The BDF and FAME fuels contain about 11% oxygen, making them so called oxygenated fuels.

Table 2 shows the FAME compositions of the BDF measured by a gas chromatographic method. As shown in Table 2, the major component of the BDF made from rape oil is OME. The palm oil BDF contains OME and PME, in similar proportions.

Figure 1 shows the distillation characteristics with the three kinds of BDF and gas oil; the BDF was analyzed by a gas chromatographic method (ASTM D2887). The BDF contains no lower boiling point components, and the evaporation characteristics are poorer than ordinary gas oil. The palm oil BDF contains more of lower boiling point components than the others, because the boiling point of PME, a major component of palm oil BDF, is somewhat lower than that of OME.

The present study also employed mixed OME-PME blends that are represented as OMEP**; the ** shows the PME content (mass %) of the mixture. For example, OMEP33 is a fuel with OME: PME=2:1. The experiments used three blends: neat OME, OMEP33, and OMEP50.

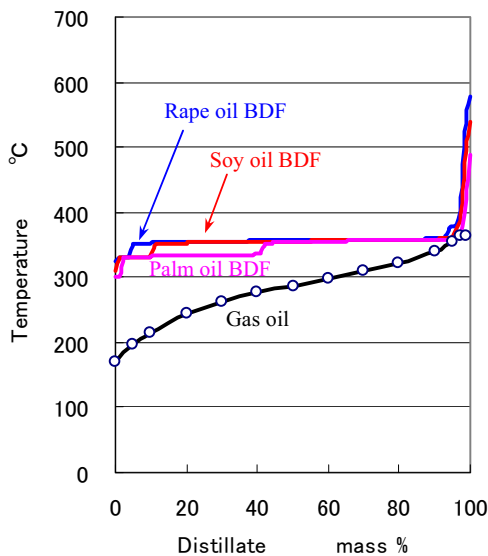


Figure 1 Distillation characteristics

Table 3 Engine specifications

Engine type	4 stroke, Horizontal, Water cooled
Stroke volume	411 cc (Single cylinder)
Compression ratio	18
Combustion chamber	DI (Toroidal type)
Rated output	5.1kW/2400rpm (BMEP=0.62MPa)
Injection pump	Bosch PFR (Plunger 7mm)
Injection nozzle	DLLA 150 (4-φ0.2)
Opening pressure	21.7MPa
Injection timing	Fixed (19°C A.BTDC)

ENGINE SETUP – The experimental engine is a 4 stroke, naturally aspirated, water-cooled single cylinder direct injection diesel engine equipped with a toroidal type combustion chamber and the principal specifications of the engine and its fuel injection system are shown in Table 3. During the experiments, the engine was operated with $85 \pm 2^\circ\text{C}$ cooling water and $70 \pm 2^\circ\text{C}$ lubricating oil at a constant engine speed of 1900rpm which corresponds to the maximum brake torque conditions. The combustion pressure was measured with a strain gauge type pressure pick-up and the crank angle was detected by a rotary encoder. The two signals were input into a personal computer, and the rate of heat release was determined from the average pressure of 50 cycles. The stability of combustion was evaluated with the cycle to cycle variation in maximum combustion pressure, P_{max} . The maximum combustion pressure was recorded through about 100 cycles, and the combustion fluctuation was defined as the standard deviation in the distribution of P_{max} divided by the mean

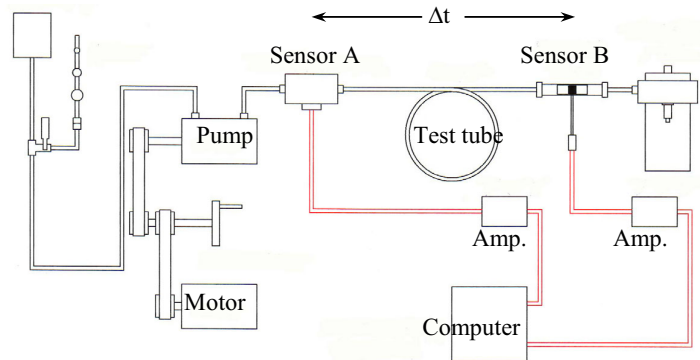


Figure 2 Experimental apparatus for the speed of sound measurements

value of P_{max} . The NOx emissions were measured using a CLD analyzer, the HC was measured as ppm propane using an FID analyzer, and smoke density was measured with a Bosch smoke meter.

MEASURING APPARATUS FOR SPEED OF SOUND – To establish the influence of the kind of fuel on the injection characteristics, the isothermal compressibility was examined. The present study investigated the differences in bulk modulus by measuring the speed of sound in the fuel with the FAME fuels and ordinary gas oil. The bulk modulus is defined by equation (1), and the relation between bulk modulus and the speed of sound in a fuel is shown by equation (2).

$$E = \rho \frac{dP_f}{d\rho} \quad (1)$$

$$E = a^2 \rho \quad (2)$$

Where, E : bulk modulus, Pa
 ρ : fuel density, kg/m^3
 P_f : fuel pressure, Pa
 a : speed of sound in fuel, m/s

As suggested by equation (2), the bulk modulus can be estimated from the speed of sound and the fuel density which are determined as functions of fuel pressure and temperature. Figure 2 shows the experimental apparatus for the speed of sound measurements. Pressure signals were detected with two sensors which were installed far apart (8430 mm) in a stainless steel test tube. When fuel is injected into the tube, which is filled with the fuel, a pressure rise occurs at each sensor position. The speed of sound was determined from the time difference, Δt between the signals of sensor A and sensor B. The measurements of the speed of sound were conducted at fuel pressures of 4 to 40 MPa with FAME and gas oil.

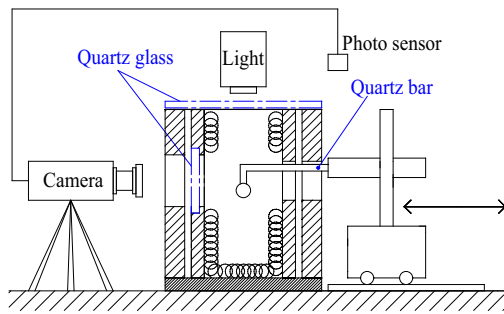


Figure 3(a) Experimental apparatus for determining combustion characteristics of suspended fuel droplets

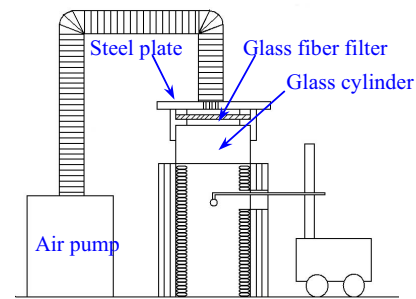


Figure 3(b) Experimental apparatus for soot measurements using suspended fuel droplets

EXPERIMENTAL APPARATUS FOR SUSPENDED DROPLET COMBUSTION – Figure 3 shows the experimental apparatus for the combustion of suspended fuel droplets: Figure 3(a) is for the combustion characteristics study and Figure 3(b) is for the soot formation study. The electric furnaces have a 50 mm inner diameter and 100 mm high cylindrical chamber, heated from below and around the chamber. With a micro syringe, an appropriate volume of fuel (1 μL for the combustion characteristics [Figure 3(a)] and 1.6 μL for the soot formation [Figure 3(b)]) was suspended at the tip of the quartz bar with the spherical suspending part (0.6 mm diameter), and the droplet was manually placed, quickly, in the chamber. The initial ambient temperature was measured by a C.A. thermocouple at the center of the chamber. The mean air fuel ratio was about 70 at the ambient temperature 860°C when the gas oil droplet was used. The evaporation and combustion behaviors of the fuel droplets were analyzed with images taken by a high speed video camera at a constant speed of 100 fps. As shown in Figure 3(a), there are two windows on opposite sides of the cylindrical chamber: one for the inlet port to the quartz bar, 4 mm wide 20 mm long, and the other is for the observations, with a 10 mm×40 mm quartz glass window. The top of the chamber was covered with quartz glass and light was introduced here. When droplets pass the inner furnace wall, the heating starts by the radiation from the heater. This is defined as the start of heating and a photo sensor started the high speed video camera. It is well known that during the combustion process of fuel droplets with mono-component hydrocarbon fuels or lighter petroleum products such as gas oil, the values of d^2 decrease linearly with time, t [23]. Therefore the relation between d^2 and t of the various fuel droplets was analyzed using the images taken. The droplets were assumed to be ellipsoidal and equations (3) and (4) were employed:

$$d = 2 \left[\frac{3(V - V_0)}{4\pi} \right]^{\frac{1}{3}} \quad (3)$$

$$V = \frac{\pi}{6} d_1 d_2^2 \quad (4)$$

Where, d : diameter of suspended droplet, mm
 V : gross volume of droplet, mm^3
 V_0 : volume of suspending quartz bar enveloped by droplet, mm^3
 d_1 : length of major axis of the ellipse, mm
 d_2 : length of minor axis of the ellipse, mm

For the soot formation study, the soot was trapped on a glass fiber filter as shown in Figure 3(b). The filter was 70 mm in diameter and was mounted above the electric furnace in an aluminum alloy holder. A heat-resistant glass cylinder, 75 mm inner diameter and 70 mm high, was set between the furnace and the filter holder. To trap all the formed soot, the ambient gas was evacuated with an air pump (vacuum cleaner) via a 3 mm thick steel plate (with 23- ϕ 3 holes) just after the ignition. The soot quantity was determined from the mass of the filter, with a microbalance (sensitivity, 0.01mg) before and after the combustion. As the soot quantity per combustion event is extremely small, the present experiments used ten continuous combustions before a filter was removed for analysis. To obtain accurate data, careful pre-treatment of the glass fiber filter was performed: prior to the experiments, water contained in the filter was removed by maintaining the filter in a drying chamber at 200°C for more than 20 minutes.