

A Comparative Analysis on Engine Performance of a Conventional Diesel Fuel and 10% Biodiesel Blends Produced from Coconut Oils

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ABSTRACT

This paper presents engine performance and emissions of coconut oil-derived 10% biodiesel blends in petroleum diesel demonstrating simultaneous reduction of smoke and NO_x emissions and increased brake power. The experiments were performed in a single-cylinder version of a light-duty diesel engine for three different fuels including a conventional diesel fuel and two B10 fuels of chemical-catalyst-based methyl-ester biodiesel (B10_{mc}) and biological-catalyst-based ethyl-ester biodiesel (B10_{eb}). The engine tests were conducted at fixed speed of 2000 rpm and injection pressure of 130 MPa. In addition to the fuel variation, the injection timing and rate of exhaust gas recirculation (EGR) were also varied because they impact the combustion and thus the efficiency and emissions significantly. For each operating condition, the in-cylinder pressure traces were recorded using a piezo-electric pressure transducer, which was used to calculate the indicated mean effective pressure (IMEP), apparent heat release rate (aHRR), burn duration. The brake MEP (BMEP) was calculated from a brake torque reading in the EC dynamometer, which was then used to obtain friction MEP (FMEP) as the difference between IMEP and BMEP. The results show lower IMEP for B10_{mc} and B10_{eb} than that of petroleum diesel, which is expected considering the lower calorific value of B10 fuels. However, the BMEP of B10_{mc} displays a comparable value to that of petroleum diesel. The reason for this unexpected observation is likely enhanced lubrication and thus reduced frictional loss because the addition of coconut-derived biodiesel compensates for the reduced IMEP. This effect is higher when B10_{eb} is used, showing even higher BMEP than the petroleum diesel fuel, particularly at the earliest and latest injection timings. The advantages of B10_{eb} over B10_{mc} as well as petroleum diesel are also evident in the engine-out emissions. The emission results show that the smoke emissions are significantly lower for B10_{eb} than those of B10_{mc} or the petroleum diesel. The NO_x emissions of B10_{eb} are also lowest among the tested fuels. This finding is significant because B10_{mc} show higher NO_x emissions than the diesel fuel and B10_{eb} . Another interesting finding from the experiments was the fact that EGR can be more effective in achieving further NO_x reduction when B10_{eb} was used than the petroleum diesel. For tested conditions of this study, the EGR tests demonstrate that B10_{eb} achieves 10% opacity and 4 g/kWh NO_x emission, which are lower than 20% opacity and 5.5 g/kWh NO_x emission of the petroleum diesel. Therefore, B10_{eb} in this study not only demonstrate a benefit in increasing the brake power of a conventional diesel fuel but also in simultaneously reducing smoke and NO_x emissions.

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INTRODUCTION

Biodiesel is an alternative diesel fuel typically produced by blending with modified vegetable oils and animal fats [1]. Although food versus fuel is still a confining issue, current opportunities exist for renewable biodiesel due to continuing high prices of imported liquid fuels, as well as environmental concerns over the increasing use of fossil fuels. As a result, many countries have developed programme to increase the biodiesel supply to 5~10% of the total diesel supply by the 2020s [2, 3, 4]. The increased biodiesel supply will not only increase the use of renewable fuels but also reduce the engine-out smoke emissions, which are strictly regulated emissions for diesel

engines. This is achieved because biodiesel is oxygenated and therefore the soot formation rate is low [5, 6] while the oxidation rate is high [7, 8].

Among various biodiesel feed stocks [2, 4, 6, 9, 10], coconut oil is of particular interest in this study. Coconuts are abundant in many tropical areas and have higher oil productivity than that of oil seeds [11]. Coconut oil is composed of 91% saturated fatty acids and 79% of them are medium chain length (C6~C14) hydrocarbons [11, 12]. This molecular structure contributes to higher oxidation stability of coconut-based biodiesels, compared to those of other biodiesels (e.g. from soybean, rapeseed or animal fats) [13]. Another benefit of the

coconut biodiesel is its reduced engine-out smoke emissions, even compared to other biodiesels, largely due to its very small (9%) concentration of unsaturated fatty acids with double bonds structures [14].

As for other biodiesels, however, coconut oil cannot be used in existing engine hardware due to its higher viscosity compared to that of conventional diesel fuels [2, 13, 15, 16]. Therefore, trans-esterification of the fats (triglycerides) into biodiesel is widely used to reduce the viscosity [1, 2, 13, 16]. This is typically achieved through an alkali catalytic conversion process (typically using methanol) [1, 7, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31]. An alkali-catalysed conversion process can have a high production rate; however, it can result also in the saponification. Furthermore, the chemical catalyst is not reusable [32, 33]. In our recent study [11, 34], the enzymatic (lipase) conversion of coconut oil for biodiesel production has been described as an alternative to such chemical conversion processes. The findings were promising as a lipase-catalysed process showed reduced saponification of the relatively high free fatty acid (FFA) content, when compared with an alkali-catalysed process. Moreover, the lipase catalyst could be reused several times after being washed by water. Another benefit was that for the separation process, additional treatment (e.g. waste water treatment and adsorptive post-treatment) was not required to separate the biodiesel from the glycerol due to the high purity of the enzyme reaction [35]. We also used ethanol instead of methanol during the trans-esterification process. The use of ethanol has advantage over methanol because it can be produced from biomass, is less toxic and has lower risk of explosion [35, 36]. Moreover, our lipase-catalysed conversion using ethanol showed a higher conversion rate when compared to biodiesel production using methanol [11], which was expected given that ethanolysis is more effective than methanolysis for an enzyme catalyst [35, 36].

The current study aims to evaluate the engine performance and emissions of this coconut-based biodiesel produced by an enzymatic conversion process using ethanol. For comparison with the lipase-catalysed ethyl-ester biodiesel, engine tests were carried out also on a traditional alkali-catalysed methyl-ester biodiesel. Due to the lower calorific value of biodiesel compared to petroleum diesel, lower brake power values in engine tests were expected, with previous studies showing a varying degrees (5~20%) of power reduction depending on the source of oils and production processes [1, 18, 19, 20]. The source oil and production process can also impact on the engine-out emissions. While reduced smoke emissions are consistently reported in previous studies, there are mixed conclusions in the emission concentration of nitrogen oxides (NO_x : NO and NO_2). Some authors have reported increased NO_x emissions [4, 19, 21, 22, 23, 37, 38, 39, 40] while others found reduced NO_x emissions [8, 24, 25, 26, 41, 42, 43]. Therefore, the need was clear for detailed engine tests of our new biodiesel produced from coconut oil using ethanol addition and a lipase catalyst.

Detailed engine tests were conducted in an automotive-size, single-cylinder research diesel engine equipped with a modern common-rail fuel injection system, enabling independent controls of injection pressure and timing. Three different fuels were tested including two 10% blends of coconut-based biodiesel produced using a biological (lipase) catalyst and ethanol (named B10_{eb}) as well as a chemical (alkali) catalyst and methanol (named B10_{mc}), and a conventional diesel fuel. Low 10% blends were selected to minimise the potential hardware damage due to unknown fuel issues before higher blending ratio biodiesels are tested in the future studies. Prior to the engine tests, the injection rate profile was measured using a Bosch-type injection rate meter for all fuels tested in the present study. In the engine, various performance parameters were measured including in-cylinder pressure, power-shaft torque and engine-out emissions of smoke, NO_x , carbon monoxide (CO) and unburned hydrocarbon (HC). In addition to fuel variations, fuel injection timing and a rate of exhaust gas recirculation (EGR) were also varied to understand the impact of these emissions control parameters on the engine performance and emissions of tested B10 and diesel fuels.

EXPERIMENTS

Fuels

Fig. 1 shows schematics for trans-esterification processes of B10_{mc} and B10_{eb} tested in this study. The low blending ratio was used because it is close to the commercial applications and can minimise the issues in hardware compatibility. B10_{mc} was a blend of 90% petroleum diesel and 10% biodiesel produced through the trans-esterification of coconut oils using methanol and NaOH. The schematic also show glycerol, a by-product of trans-esterification process. In comparison, B10_{eb} was a blend of 90% petroleum diesel and 10% coconut-based biodiesel produced with a lipase and ethanol. As explained in our previous work [34], the 5:1 volume ratio of coconut oil and ethanol were mixed before a lipase enzyme was added for a rate of 1 g per 100 mL ethanol. The reaction temperature was held constant at 50°C for 50 hour incubation. Ultrasonic waves were used as an additional means to overcome a lower production rate of the lipase catalyst than that of alkali catalysts. Variations in the fuel production processes influenced the fuel properties. Table 1 summarises important properties of all tested fuels in the present study, together with the Australian biodiesel standard and relevant test methods. The properties of B10 fuels were calculated using the known properties of petroleum diesel and the measured values for neat biodiesels [11]. From Table 1, it is seen that most fuel properties of 10% biodiesel blends are similar to those of petroleum diesel; however, the viscosity shows marked variations such that B10_{mc} has 76% higher viscosity (3.35 mm²/s) than that of petroleum diesel (1.90 mm²/s). Also, this is 14% higher than B10_{eb} with 2.94 mm²/s kinematic viscosity. Since higher viscosity can increase the frictional loss [1], this might result in reduced brake power even if a lower calorific value was compensated by the increased injection mass [41].

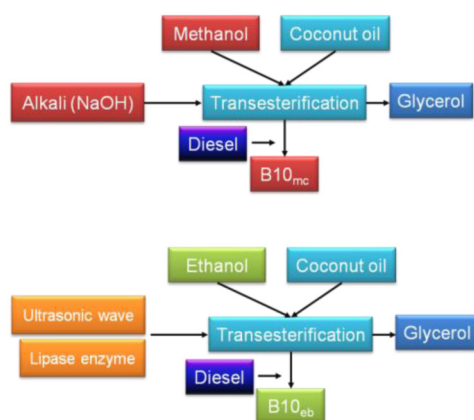


Figure 1. Schematic diagram of biodiesel blends production.

Table 1. Fuel properties.

Fuel	Petroleum diesel	B10 _{mc}	B10 _{eb}	Australian neat biodiesel standard	Test Methods
Density @ 15°C (g/cm ³)	848	851	849	860-890	ASTM D1298
Kinematic viscosity @ 40°C (mm ² /s)	1.90	3.35	2.94	3.5-5.0	ASTM D445
Flash point (°C)	>61.5	66.2	66.2	>120	ASTM D93
Cetane number	51	-	-	>51	ASTM D613
Sulphur content (ppm)	10	-	-	< 10mg/kg	ASTM D5453
Calorific value (MJ/kg)	41.66	41.35	41.39	N/A	ASTM D240
CHO wt. %	C	84.91	83.30	83.71	N/A
	H	15.09	15.20	14.791	N/A
	O	0	1.52	1.50	N/A
Stoichiometric air/fuel ratio	14.90	14.83	14.83	N/A	N/A

Table 2. Engine specifications and operating conditions.

Engine Specifications	
Displacement (single cylinder)	497.8 cm ³
Bore	83 mm
Stroke	92 mm
Piston	Cylindrical bowl (55 mm in diameter)
Number of valves	2 intake and 2 exhaust
Compression ratio (geometric)	17.7
Swirl ratio	1.4
Injection system	7-hole Bosch common-rail hole diameter (nominal): 134 µm K-factor: 1.5 Discharge coefficient: 0.86 HFR: 400 cm ³ for 30 s Included angle: 150°
Operating Conditions	
Engine speed	2000 rpm
Coolant temperature	90°C
Intake air temperature	27°C
Injection pressure	130 MPa
Injection mass (mg)	Diesel: 27.19, B10 _{mc} : 26.04, B10 _{eb} : 25.93 mg
Injection timing	18 ~ 3°CA bTDC

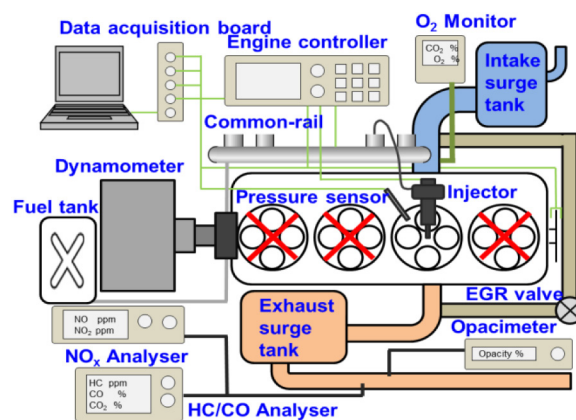


Figure 2. Diesel engine setup and measurement techniques.

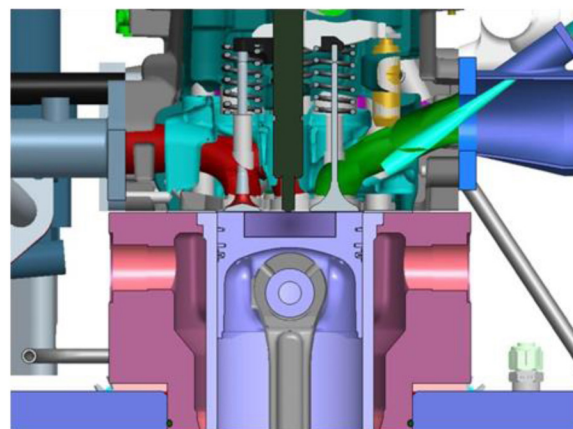


Figure 3. Combustion chamber geometry.

Single-Cylinder Diesel Engine and Operating Conditions

Fig. 2 shows an experimental setup of a single-cylinder diesel engine and measurement tools used for fuel tests. Engine specifications and operating conditions are listed in Table 2. The engine was modified from a 2-litre, four-cylinder production engine so that only one cylinder was activated. The cylinder had displacement volume of 497.8 cm³ with 83 mm bore and 92 mm stroke. The piston had a cylindrical bowl with 55 mm in diameter. On the flat cylinder head, two intake and two exhaust valves were located, as shown in Fig. 3. This combustion chamber design results in a compression ratio of 17.7, which is relevant to many production engines in the market. The intake port passage of the tested engine enabled a swirl flow with a mean flow speed to piston speed ratio (i.e. swirl ratio) of 1.4. Upstream of the intake manifold and downstream of the exhaust manifold, 60-litre surge tanks were installed to minimise pressure fluctuations associated with the single-cylinder operation.

For fuel injections, a Bosch common-rail fuel system was used for all fuels tested in the present study. A solenoid-type 7-hole injector was mounted on the engine head at the centre of the cylinder. The nominal hole diameter of the used injector was 134 µm. The nozzle hole was hydro-eroded and tapered resulting in 1.5 “K-factor” [= (inlet diameter - outlet diameter)/10], from the manufacturer's specification. The discharge coefficient of this nozzle hole was 0.86 (for diesel fuel) and the tested hydraulic flow rate (HFR) was 400 cm³ for 30 seconds.

at 10 MPa fuel pressure. The included angle between holes was 150°. The injection pressure, duration and timing were controlled independently through a universal injection controller (Zenobalti ZB-9013P).

The engine was operated at fixed speed of 2000 rpm at which the base production engine generates the maximum torque. An eddy current dynamometer (Froude Hoffmann, AG-30HS) was used for this operation. The coolant temperature was controlled at 90°C by a water temperature controller/circulator (ThermalCare Aquatherm) to simulate warmed-up engine conditions. A thermocouple was used to monitor intake air temperature throughout the experiments, which indicated 27°C with minimal variations. The fuel injection pressure was fixed at 130 MPa and the injection duration was held constant at 0.65 ms (electronic). It was noted that variations in fuel density and calorific values of tested fuels were very minimal, due to low 10% blending ratio. However, for the fixed injection duration, we measured slightly lower injection mass of about 26 mg for B10_{mc} and B10_{eb} than that of petroleum diesel (27.19 mg). This slightly lower injection mass of B10 fuels could be due to higher viscosity that would increase the friction within the nozzle hole and thus decrease the discharge coefficient. However, the difference was well within the injection-to-injection variations of a typical common-rail injector and the impact of this injection mass variation on the fuel energy (=calorific value multiplied by the injection mass) was very minimal. For each fuel, the injection timing was swept from 18 to 3°CA bTDC to evaluate the combustion phasing and its sensitivity to fuels. Also, the EGR rate was varied from 0 to 30% to test its effect on NO_x emission reduction. The EGR rate in this study was estimated using measured carbon dioxide (CO₂) concentration in the intake and exhaust pipe (i.e., CO₂^{intake}/CO₂^{exhaust}).

Measurements

A piezo-electric pressure transducer (Kistler 6056A) was used to measure the in-cylinder pressure traces. The pressure data were recorded for 100 cycles for each engine operating condition and then used to obtain an average pressure trace, indicated mean effect pressure (IMEP), and the coefficient of variation of IMEP (CoV of IMEP). The apparent heat release rate (aHRR) was also calculated from the in-cylinder pressure trace. From the aHRR trace, the ignition delay was estimated by reading the time between the start of injection (SOI) and the start of combustion (SOC). In this study, the measured injection rate was used for SOI and the crank angle location for 10% heat release (i.e. CA10) was defined as SOC. The aHRR trace was also used to analyse combustion phasing using CA50. The burn duration was calculated for both the initial burn (CA10 to CA50) and late-cycle burn (CA50 to CA90). For each engine operating condition, engine-out emissions were measured. We used an opacimeter (Horiba MEXA-600S, accuracy: ±0.15 m⁻¹ light absorption coefficient) to measure the smoke emissions, a chemiluminescence-type gas analyser (Ecotech 9841AS, 1%

accuracy) for NO_x emissions, and a non-dispersive infrared (NDIR) analyser (Horiba MEXA-584L, 1.7% accuracy) for unburnt hydrocarbon (HC), carbon monoxide (CO) and carbon dioxide (CO₂) emissions.

Prior to the engine tests, three different fuels of petroleum diesel, B10_{eb} and B10_{mc} were measured for a fuel injection rate using a Bosch- tube-type injection rate meter, as shown in Fig. 4 (top). The injection rate meter measures the pressure deviation occurring within the fuel-filled tube, which is converted to the injection rate profile. The injection was repeated for 20 times and the averaged injection rate profiles are plotted in Fig. 4 (bottom). It is noticeable there is a measurable delay between the start of injection current and the actual start of injection. This delay, a time required to activate the solenoid valve and the needle lift, was consistently measured at 0.36 ms regardless of the fuel type. Consistent with the reduced injection mass associated with higher fuel viscosity, the injection rate profiles for B10 fuels show slightly lower peak value and thus lower integrated area than those for petroleum diesel. As mentioned previously, however, the difference did not cause significant variations in the injected fuel mass (with only ~1 mg difference). With very similar injection profiles for all tested fuels and no major hardware compatibility issues found during the injection rate measurements, the engine experiments for B10 fuels were ready.

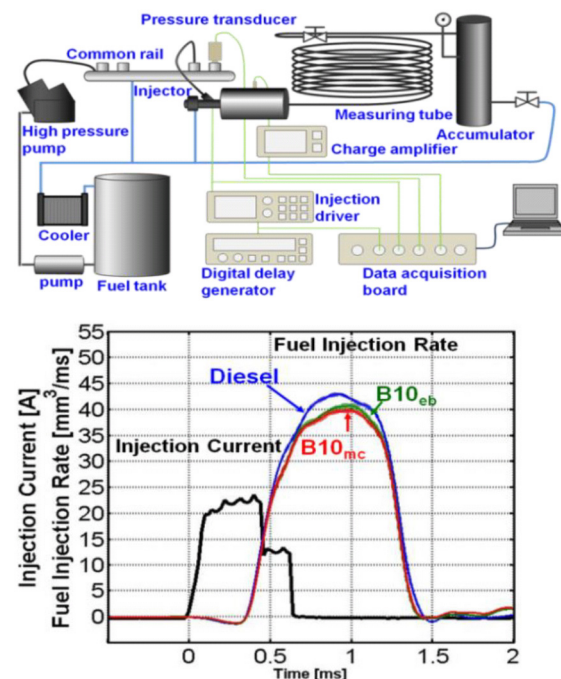


Figure 4. Bosch-type injection rate meter setup (top) and measured injection rates for petroleum diesel, B10_{eb}, and B10_{mc} fuels tested in the present study (bottom). Also shown is the injection current supplied to control the solenoid valve of the common-rail injection.