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Engine Combustion and Emissions of Coconut Oil-Based Biodiesel and Diesel Blends

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Abstract

Our previous study about 10% blend of coconut-based, lipase-catalysed ethyl ester biodiesel with diesel demonstrated a potential of reduced smoke and NO_x emissions while keeping the brake power of a conventional diesel. This study further exploits the coconut biodiesel by testing higher blending ratio fuels. The experiments were conducted in a single-cylinder, small-bore diesel engine for three different blending ratios including diesel (B0), B25 and B40. The injection rate measurement was also performed for all tested blends to find the fuel mass per injection for the same total energy considering lower calorific value of biodiesel. The engine was run at fixed speed of 2000 rpm and the injection pressure of 130 MPa while the injection timing was varied. The in-cylinder pressure traces were monitored by a piezo-electric pressure sensor. This recorded data was used to calculate the apparent heat release rate (aHRR), indicated mean effective pressure (IMEP), and burn duration. The brake MEP (BMEP) was also calculated from the measured brake torque in the EC dynamometer and in turn friction MEP (FMEP). The results showed that the IMEP decreases with an increasing blending ratio due to increased burn duration (or slower reaction) of lower calorific value biodiesel. However, the BMEP increased or stayed the same because the improved lubricity of high biodiesel blends caused reduced FMEP and thus cancelled out the IMEP decrease. The benefits of high biodiesel blends were also found in engine-out emissions. Interestingly, not only smoke emissions but also NO_x emissions were decreased with an increasing biodiesel blending ratio. It was explained that the oxygenated biodiesel suppressed soot formation as well as promoted soot oxidation, resulting in reduced engine-out smoke emissions. Also, the slower reaction of high biodiesel blends as well as shorter carbon chain length of coconut-based biodiesel led to the reduced combustion temperature and thereby decreasing NO_x emissions. Therefore, the high biodiesel blends using coconut oil feed stock are very promising alternative fuels to overcome the smoke-NO_x trade-off of a conventional diesel while maintaining the brake power.

Introduction

Biodiesel is an alternative fuel to a conventional diesel fuel, which is produced from various feed stocks. In some countries, the biodiesel supply is mandated, requiring 5% to 20% of diesel to be replaced by biodiesel [1-4]. In the US, soybean is a common feedstock whereas in Europe rapeseed is widely used [5, 6]. These feed stocks, however, can increase the crop price, raising a food versus fuel issue [6, 7]. While second-generation, cellulosic feed stocks such as starches, woody chips or algae are actively investigated, some countries within the tropics utilise coconut oils as they are abundant in the region.

In addition to the diversification of fuel supplies, the reduced smoke emissions are a great advantage of biodiesel fuels [8-13]. However, there are different conclusions on NO_x emissions for some studies reporting the increased NO_x [8-11] whereas others showing the reduced NO_x emissions [12,13]. Our previous study [14] on 10% biodiesel blends produced from coconut oil (B10) agreed with the latter case, demonstrating the simultaneous reduction of smoke and NO_x emissions compared to a conventional diesel fuel. This was because coconut biodiesels consist of short carbon chain hydrocarbons leading to the decreased flame temperature and thus reduced NO formation. The coconut biodiesel blend also showed the same brake power of diesel despite the lower IMEP associated with longer burn duration. A likely cause for the observed trend was the enhanced lubricity and thus reduced frictional loss.

Since the coconut oil-based B10 fuel showed such potential, the motivation was clear for higher blending ratio coconut biodiesels. This study presents the results of higher blends including B25 and B40 tested in a single-cylinder, light-duty, common-rail diesel engine. In-cylinder pressure and brake torque were recorded throughout the experiments. Engine-out emissions such as smoke and NO_x were also monitored.

Experiments

The properties of neat biodiesel and petroleum diesel for this study are listed in table 1. The density of neat biodiesel is slightly higher than petroleum diesel while the viscosity is twice higher. The biodiesel has lower calorific value than that of petroleum diesel. To compensate the lower fuel energy, higher fuel mass was injected for biodiesel blends. Therefore the total energy was fixed at 1080 J. The injection mass was measured using a Bosch tube-type injection rate meter.

Figure 1 shows the experimental setup for the engine tests. The engine was naturally aspirated and shared the production engine head with a second-generation Bosch common-rail system. In the intake and exhaust, 60-litre surge tanks were used to minimise the pressure fluctuations. The fuel injection was controlled using a universal controller (Zenobalti ZB-9013P). A piezo-electric pressure transducer (Kistler 6056A) was used to record crank-angle-resolved in-cylinder pressure. Simultaneously, the emissions of smoke (Horiba Opacimeter MEXA-600S) and NO_x (Ecotech 9841 AS) were measured.

The engine specifications are summarised in table 2. The engine has a single-cylinder displacement volume of 497.8 cm^3 with 83 mm bore and 92 mm stroke. The compression ratio is 17.7 with 1.4 swirl ratio produced by two swirling intake ports. The engine was connected with an eddy current (EC) dynamometer (Froude Hoffmann, AG-30HS) and operated at fixed speed of 2000 rpm at

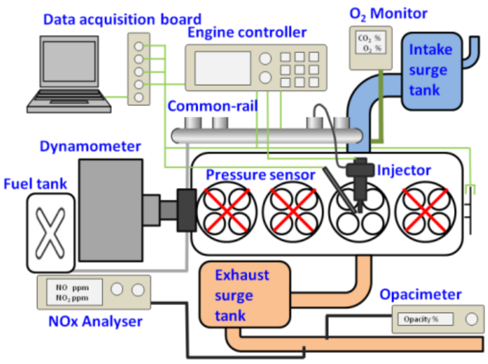

Figure 1. Schematic diagram of single cylinder diesel engine and diagnostic tool.

which the maximum torque of the production engine is measured. The coolant temperature (90℃) was held constant by using a water temperature controller and circulator (Thermalcare Aquatherm RS series). The intake air temperature was monitored and throughout the experiments it was fixed at 27℃. The injection pressure was also fixed at 130 MPa. In addition to fuel variations, two different injection timings of -13 and -3 crank angle degrees after top dead centre (°CA aTDC) were tested for the combustion phasing variations.

Fuel		Petroleum diesel	B100
Density @ 15℃ (g/cm^3)		848	860
Kinematic viscosity @40 ℃ (mm^2/s)		1.9	3.8
Flash point (℃)		>61.5	108.5
Cetane number		51	-
Calorific value (MJ/kg)		41.66	39
CHO wt.%	Carbon	84.91	73.68
	Hydrogen	15.09	12.28
	Oxygen	0	14.04

Table 1. Fuel properties

Engine Specifications	
Displacement	497.8 cm^3
Bore	83 mm
Stroke	92 mm
Compression ratio	17.7
Swirl ratio	1.4
Number of valves	2 intake and 2 exhaust
Injection system	7-hole Bosch common-rail Nominal hole diameter: 134 µm K-factor: 1.5 Discharge coefficient: 0.86 HFR: 400 cm^3 for 30s Included angle: 150°
Operating Conditions	
Engine speed	2000 rpm
Coolant temperature	90℃
Intake air temperature	27℃
Injection pressure	130 MPa
Injection timing	-13° and -3℃A aTDC

Table 2. Engine specification and operating conditions

Results and Discussion

Figure 2 shows the in-cylinder pressure (top) and apparent heat release rate (aHRR, bottom) for three biodiesel blends (diesel, B25 and B40) and two different injection timings tested in the present study. Marked differences in the in-cylinder pressure and aHRR are observed for the injection timings such that the advanced injection leads to earlier combustion phasing. Since the high heat release occurs near top dead centre (TDC), the advanced injection resulted in higher peak pressure than the late injection. However, the ignition delay was shorter for the advanced injection due to higher ambient gas temperature and density at the time of fuel injection. This resulted in less pre-combustion mixing and thereby reducing the peak aHRR. The lower peak aHRR typically represents lower combustion temperature and thus NO formation can be less for the advanced -13℃A aTDC injection despite high in-cylinder pressure.

Compared to the significant influence of injection timing variations on the in-cylinder phenomena, the biodiesel blending ratio appear to make a minimal impact, particularly for the advanced injection timing. When the late injection case is closely looked at, however, the rise of aHRR occurs slightly earlier and the peak aHRR decreases with an increasing biodiesel blending ratio. This was likely due to higher ignition quality (higher cetane number) of biodiesel fuels that led to the decreased ignition delay.

The in-cylinder pressure traces in figure 2 were used to estimate the indicated mean effective pressure (IMEP). The results are plotted in figure 3. A noticeable trend is observed in the figure such that IMEP of the advanced injection timing shows much higher value than that of the late injection timing. This was due to the combustion phasing that was positioned just after TDC for

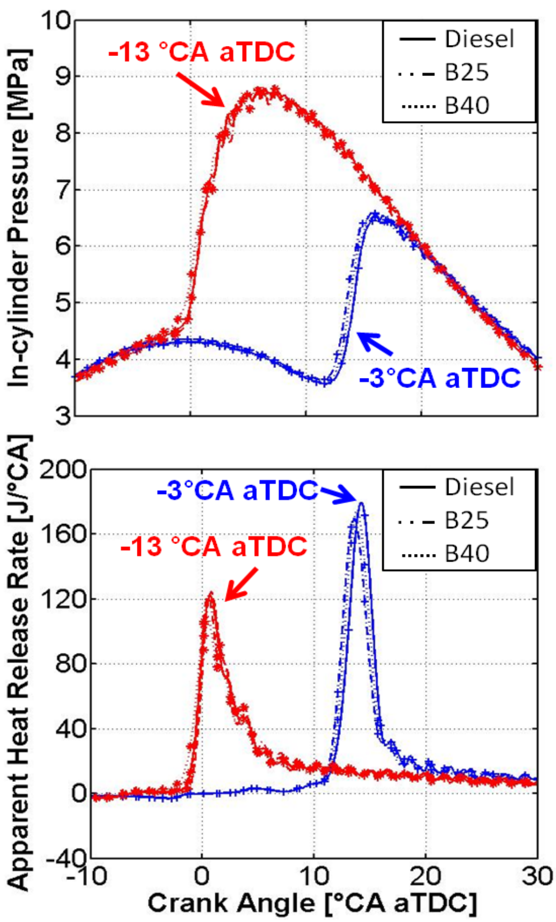

Figure 2. In-cylinder pressure (top) and aHRR (bottom) for three different coconut biodiesel blends and two different injection timings

-13°CA aTDC injection, which caused higher in-cylinder pressure and thus higher IMEP. Another interesting trend from figure 3 was that the higher biodiesel blends show lower IMEP for both injection timings. To explain this trend, burn durations were calculated using the aHRR data presented in figure 2. The results are shown in figure 4. The burn duration was measured by reading the crank angle locations of 10% and 90% of the total heat release. The figure shows that the burn duration increases with an increasing biodiesel blending ratio. This was likely due to

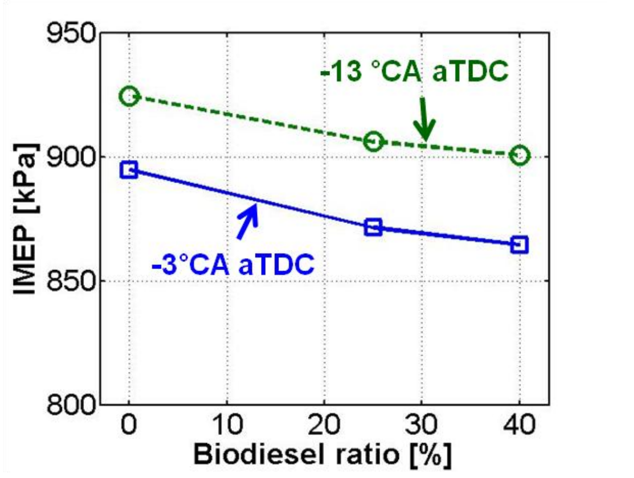

Figure 3. IMEP for three different coconut biodiesel blends and two different injection timings

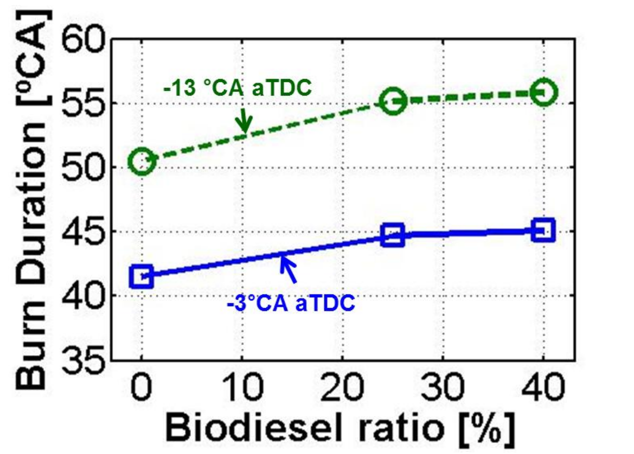

Figure 4. Burn duration for three different coconut biodiesel blends and two different injection timings

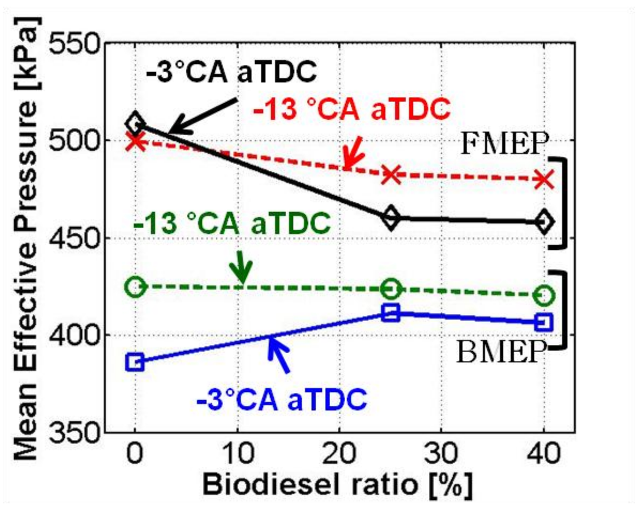

Figure 5. BMEP and FMEP for three different coconut biodiesel blends and two different injection timings

the lower calorific value of biodiesel fuels, which decelerated the reaction. The slow reaction could not produce high indicated power in piston engines.

The reduced IMEP of high biodiesel blends could result in decreased BMEP since the brake power is a difference between the indicated power and frictional loss. However, figure 5 shows that the BMEP does not decrease but maintains the same value of diesel (~425 kPa) for the advanced injection. For the later injection timing, the BMEP in fact increases with an increasing biodiesel blending ratio. The improved lubricity of the coconut oil-based biodiesel of the present study and its positive impact on the reduced FMEP was demonstrated in our previous study [14]. Figure 5 confirms once again that the IMEP reduction (figure 3) for high biodiesel blends can be compensated by reduced FMEP.

Between two injection timings, figure 5 shows lower FMEP values for -3°CA aTDC injection when B25 and B40 are tested. The reason for this difference is not entirely clear but it could be that the lower in-cylinder pressure and the combustion occurring late in the expansion stroke (figure 2) further reduced the frictional loss, compared to high pressure, near TDC combustion for -13°CA aTDC injection. Figure 5 also shows that despite the lower FMEP, the higher IMEP of the advanced injection timing (figure 3) resulted in higher BMEP for a fixed biodiesel blending ratio. Due to much higher IMEP of the advanced injection, the trend could not be reversed. Therefore, the advanced injection is preferred to achieve high brake power when higher biodiesel blends are used in a diesel engine.

The same or increased BMEP with an increasing biodiesel blending ratio shown in figure 5 is a great advantage over a conventional diesel fuel. Engine developers often compromise the brake power to reduce the smoke emissions below the regulation. If low-smoke fuel is used, higher brake power engine setup becomes possible. Figure 6 (top) shows the dramatic reduction of opacity (smoke emissions) with an increasing biodiesel blending ratio. This was due to a well-known effect of oxygenated fuels on suppressed soot formation and enhanced soot oxidation. Also high-sooting aromatic contents are much

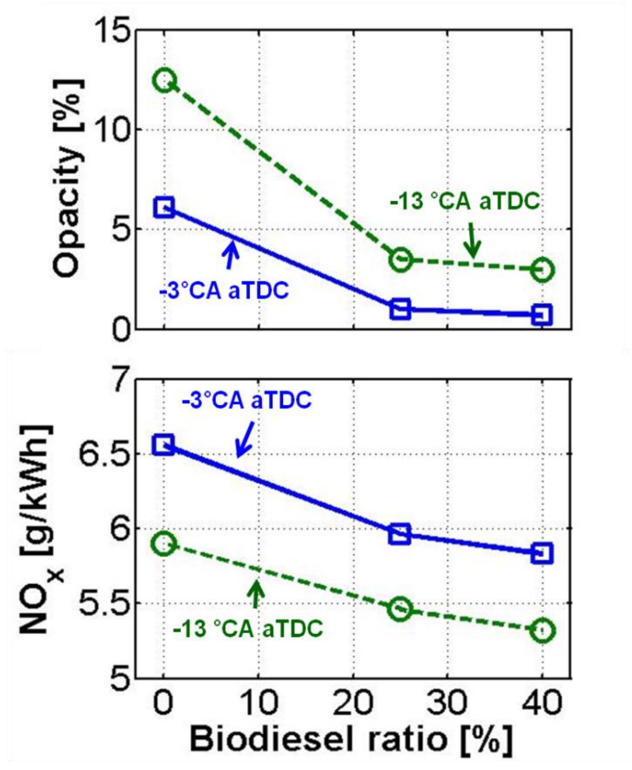

Figure 6. Smoke opacity (top) and NO_x emissions (bottom) three different coconut biodiesel blends and two different injection timings

less in biodiesels than a conventional diesel fuel, which further suppressed the soot formation. In the present study, over 70% reduction of smoke emissions is achieved for B40 regardless of the fuel injection timing.

Between different injection timings, the advanced injection (-13°CA aTDC) with less premixed combustion (see figure 2) shows higher smoke emissions at a fixed biodiesel blending ratio. However, the trend is reversed for NO_x emissions. Figure 6 (bottom) shows higher NO_x emissions for -3°CA aTDC injection than that for -13°CA aTDC injection. As mentioned previously (figure 2), the higher peak aHRR of the late injection timing and thus higher combustion temperature caused the increased NO formation via thermal Zeldovich mechanism.

For the biodiesel blending ratio variations, figure 6 (bottom) shows decreasing NO_x emissions with an increasing biodiesel blending ratio. For example, the NO_x emissions were reduced by 10% for B40 regardless of the fuel injection timing. This once again is consistent with the peak aHRR trends as shown in figure 2, *i.e.* lower peak aHRR and hence reduced combustion temperature. During the mixing-controlled combustion, the slower reaction of high biodiesel blends (figure 4) would also lead to the reduced combustion temperature and thereby decreasing NO_x emissions. In addition, the coconut-based biodiesel of this study is comprised of shorter carbon chain hydrocarbons (C6-C14) than those of a conventional diesel fuel [15]. These medium carbon chain lengths would result in lower flame temperature and thus less NO formation [16].

Conclusion

Coconut oil-derived biodiesels blended with diesel were tested in a single-cylinder, light-duty, common-rail diesel engine. The in-cylinder phenomena, brake torque and engine-out emissions were measured for three different biodiesel blends of B0 (diesel), B25 and B40 as well as two different injection timings of -13 and -3°CA aTDC. The major findings of this study are summarised as follows:

- The indicated power decreases with an increasing biodiesel blending ratio because of slower reaction and thus lower combustion temperature of coconut biodiesel. However, the improved lubricity of coconut biodiesel causes the reduced frictional loss, which outperforms the lower indicated power. This results in high brake power for biodiesel blends tested in this study.
- Simultaneous reduction of smoke and NO_x emissions are achieved using coconut biodiesel blends in the present study. The oxygenated and low aromatic biodiesel causes significantly suppressed soot formation and increased soot oxidation, resulting in reduced engine-out smoke emissions by 70%. Moreover, the slower reaction, lower peak heat release rate, and shorter carbon chain hydrocarbons in coconut biodiesel results in reduced NO formation, which achieves 10% reduction in NO_x emissions.

Acknowledgments

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