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Dependency of engine combustion on blending ratio variations of lipase-catalysed coconut oil biodiesel and petroleum diesel

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HIGHLIGHTS

- Higher coconut biodiesel blends show decreased IMEP due to slower burning.
- BMEP does not decrease significantly due to lubricity of coconut biodiesel.
- Over 70% smoke and 10% NO_x reductions are achieved for B40 compared to diesel.
- However, the BSFC increase is significant with increasing biodiesel blends.
- Biodiesel blends over 10% is not preferred for optimised BSFC and emissions.

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ABSTRACT

From our previous study about coconut oil-based biodiesel blended with petroleum diesel at a ratio of 1:9 (B10), it was found that the lipase catalysed ethyl ester B10 can achieve not only simultaneous reduction of smoke and NO_x emissions but also improved brake power compared to petroleum diesel. This paper presents engine performance of this biodiesel fuel at higher blending ratios with the expectation of further improved emissions and brake power. The experiments were performed in a single-cylinder light-duty diesel engine equipped with a common-rail injection system. Prior to the engine performance and emissions testing, the fuel injection rate measurement was conducted for various biodiesel blending ratios to find the injected fuel mass for the same total energy of 1080 J, considering 6% lower calorific value of the tested biodiesel than that of petroleum diesel. The engine experiments were performed at fixed engine speed of 2000 rpm and common-rail pressure of 130 MPa. In addition to the variations of biodiesel blending ratio, the injection timing was also swept from 13 to 3 crank angle degrees before top dead centre to evaluate combustion of biodiesel blends at various combustion phasing conditions. The in-cylinder pressure traces were measured using a piezo-electric pressure transducer, which was used to calculate key performance parameters such as the indicated mean effective pressure (IMEP), apparent heat release rate (aHRR), and burn duration. The brake MEP (BMEP) was also calculated using the measured brake torque from the eddy current (EC) dynamometer and subsequently the friction MEP (FMEP) was obtained. From the engine tests, it is found that a higher biodiesel blending ratio results in decreased IMEP because the lower calorific value of coconut oil-based biodiesel and overall leaner mixture condition cause the decreased diffusion flame temperature and extended burn duration. The improved lubricity of coconut oil biodiesel and hence reduced friction loses, however, leads to similar BMEP of petroleum diesel even for high biodiesel blends. Nevertheless, a significant increase in the brake specific fuel consumption is unavoidable at high biodiesel blending ratios. From the engine-out emission measurements, a significant reduction of smoke emissions were observed with an increase in the biodiesel blending ratio, which is explained by the oxygenated molecular structures and reduced aromatics contents of biodiesel. Also, the slower reaction and leaner mixture of high biodiesel blends, together with shorter carbon chain length of coconut oil-based biodiesel, cause the reduced flame temperature and thereby decreasing NO_x emissions. Therefore, the high biodiesel blends using coconut oil feed stock is

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very promising to overcome the smoke–NO_x trade-off of petroleum diesel. When both the brake specific fuel consumption and smoke/NO_x emissions are considered, however, the optimised biodiesel blending ratio of the tested conditions of this study is found at low B10.

1. Introduction

Biodiesel produced from rapeseed or sunflower seed in European Union [1] and soybean oil in the United States [2] penetrates into the market thanks to its renewable nature and capacity to lower greenhouse gas emissions compared to those of petroleum diesel. As of 2011, the largest biodiesel market is EU which accounts for 44% of the worldwide biodiesel production [3]. One study predicted that the global production of biodiesel will increase from 24 billion litres to 42 billion litres between 2011 and 2020 [4], which is largely driven by European government's mandate on biofuel. For example, EU requires that 10% of the total transport fuel supply should be from bio-feedstock by 2020 [5]. Due to the hardware compatibility issue, however, neat biodiesel (i.e. B100) is rare but blends of biodiesel and petroleum diesel are available in fuel stations (e.g. B2, B5 and B20 [6]). Various tests suggest that blends of 20% biodiesel (B20) and lower can be used in the existing diesel equipment with no hardware modification [7]; however, to meet the government's mandates, higher blending ratio biodiesel fuels might be required.

There are well known advantages of higher biodiesel blends in engine-out emissions. For example, many studies reported reduced smoke emissions with the increasing biodiesel blending ratio [8–16]. This is because biodiesel is an oxygenated fuel with a reduced amount of carbon compared to petroleum diesel. Oxygenated fuels yield less soot formation [17] and higher soot oxidation rates [8,10,18], leading to reduced engine-out smoke emissions. Although the increased emissions of soluble organic fractions (SOF) raise a new issue [19], the significance decrease in particulate matter emissions is a major advantage of biodiesel fuels. Similarly, the unburned hydrocarbon (uHC) and carbon monoxide (CO) emissions are reduced due to the enhanced oxidation [11,12,20,21]. Some studies, however, reported that the increased viscosity of biodiesel makes a negative impact on fuel atomisation [22], which can lead to increased uHC emissions [9].

Many studies have shown that, despite similar thermal efficiency, the engine brake power decreases with an increasing biodiesel blending ratio due to a lower calorific value of biodiesel than that of petroleum diesel [23,24]. This means higher brake specific fuel consumption (BSFC) for higher blending ratio biodiesel fuels, which is a disadvantage of using biodiesel in diesel engines [8–11,20,23–25]. Another issue is the increased engine-out emissions of the oxides of nitrogen (NO_x) for higher biodiesel blends [9,11,14,20,25–30]. From their optical diagnostics performed in a heavy-duty diesel engine to clarify the origin of increased NO_x emissions of biodiesel, Mueller et al. [31] suggested that the charge-gas mixture conditions near the flame base play a major role such that the mixtures closer to the stoichiometric at ignition cause higher local and average in-cylinder temperatures and thereby increasing thermal NO formation. From in-cylinder pressure measurements, the increased thermal NO formation shows a good correspondence with the higher peak rate of heat release [30,32], which was used to explain the increased NO_x emissions in many biodiesel studies [20,25,30]. In addition, previous studies focused on fuel molecular structures reported that the flame temperature of biodiesel fuels increases with increasing carbon chain length and unsaturation degree of fatty acids [30,33]. Therefore, it could be thought that the engine tests reporting increased NO_x emissions were conducted at charge-gas mixtures leading to higher in-cylinder temperature and using the biodiesel fuels with long carbon chain length and a high proportion of unsaturated fatty acids. The latter is further supported by the fact that many studies reporting higher NO_x emissions [11,14,20,27–31,33,34] used biodiesel fuels produced from soybean, sunflower, and rapeseed, in which unsaturated fatty acids (e.g. C18:1 and C18:2) are major components [9,35]. However, some studies [12,15,21,36] reported a directly opposite trend of the decreased engine-out NO_x emissions. Interestingly, these studies used coconut oils as a biodiesel feedstock and it is believed that short carbon chain length and a high proportion of saturated fatty acids (e.g. C12:0 and C14:0) in coconut biodiesel fuels caused lower flame temperature than that of petroleum diesel [23,30,33]. Our previous work [37] showed a consistent result such that a biodiesel blend produced from a lipase-catalysed trans-esterification process in ethanol moiety produced lower NO_x emissions than petroleum diesel due to the short carbon chain length and low flame temperature.

In addition to reduced NO_x emissions, our previous study on coconut oil-based biodiesel also demonstrated the improved brake power over petroleum diesel [37]. This was likely due to the improved lubricity of biodiesel and thus decreased friction loss in the common-rail fuel pump. The lubricity benefit of biodiesel fuels, regardless of feedstock, is well known to be caused by inherent lubrication properties from fatty acid esters [38,39]. For example, it is reported that the use of biodiesel can lead to the decreased wear and friction within the high-pressure fuel pump in which fuel provides lubrication [40–42]. Some studies also showed the reduced friction on the cylinder liner [41–46]. However, the viscosity of biodiesel fuels is also higher leading to the increased friction loss, which generally outperforms the friction loss reduction caused by the improved lubricity. It is therefore interesting that the viscosity of coconut oil biodiesel fuels is much lower than that of other widely produced biodiesel fuels (e.g. soybean, rapeseed, or sunflower [47]) and thus the positive effect of improved lubricity on reduced friction loss and increased brake power becomes measurable [37,45].

Our previous study [37], however, was focused on the impact of fuel production process on engine performance while a limited biodiesel blending ratio of 10% was used. The present work studies potential benefits of using higher blending ratio biodiesel fuels produced from the same coconut oils and production method. We conducted engine performance and emissions testing of four different biodiesel blends including petroleum diesel (B0), B10, B25, and B40. Higher blending ratios than 40% were also considered but were not tested due to decreased brake power. This will be reported in detail later in the results and discussion section. The biodiesel blends were tested in a single-cylinder, light-duty diesel engine equipped with a common-rail fuel injection system. The in-cylinder pressure and brake torque were measured while engine-out emissions of smoke (opacity), NO_x, uHC, and CO were also recorded. In addition to biodiesel blending ratio variations, the fuel injection timing was also altered, considering significant influence of combustion phasing on brake power and engine-out emissions [48–53].