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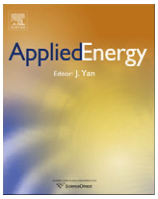

Characterisation of engine-out responses from a light-duty diesel engine fuelled with palm methyl ester (PME)

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ABSTRACT

An experimental study was conducted to evaluate the suitability of biodiesel for on-road usage based on the engine-out responses of a light-duty diesel engine. Palm methyl ester (PME) was the biodiesel fuel used in this study. The experimental programme was conducted in two separate phases. In the first phase, the effects of engine speed and load over the entire operational range on engine performance and pollutant emissions when fuelled with neat PME (B100) and a B50 PME–diesel blend were identified. Comparison was then made against that of neat fossil diesel (B0), which served as the baseline fuel. The result indicates that fossil diesel, PME and their B50 blend exhibit similar trends across the speed–load map albeit with variation in the magnitude of the responses. For the second phase, attempts were made to elucidate the on-road influence of PME content when used as blending component with diesel. This was achieved by appraising eleven fuel blends from B0 to B100 under a modified steady-state emissions test cycle, with nine intermediate blends at 10 vol.% interval in between. Conclusive reduction of tailpipe NO, UHC and smoke opacity was observed when neat PME was used, culminating in a maximum decrease of 5.0%, 26.2% and 66.7%, respectively. The influence of additional fuel-bound oxygen content in PME on CO is insignificant as diesel engine typically operates in lean mode. It can be concluded from this study that biodiesel fuels has the potential to provide part of the solution for emissions reduction in a light-duty diesel engine, both in neat and blended forms.

1. Introduction

There is an emerging trend in the passenger car sector where light-duty diesel vehicle is favoured over its gasoline-powered counterparts, especially in Western Europe [1]. In the EU alone, the number of diesel vehicles stands at 90.3 million for the year 2008 [2]. The ever-increasing number of on-road diesel vehicles has contributed significantly to the level of atmospheric urban pollutants, such as carbon monoxide (CO), nitrogen oxides (NO_x), particulate matters (PM), unburnt hydrocarbons (UHCs), aromatics and smoke [3]. These escalating levels of urban pollutants have resulted in detrimental effects on both the environment and human health [4]. Compounding these with the exhaustion of crude oil reserves, researchers around the world have intensified their search for an alternative fuel that is sustainable, economically feasible and environmentally friendly for mainstream adoption.

Biodiesel stands at the forefront as the alternative fuel of choice to fossil diesel as it can be used in existing diesel engines with few or no modifications [5,6]. Biodiesel also has the highest energy content per volume among the available alternative fuels at present [7], which is typically 10.1–24.4% lower than that of conventional fossil diesel. Furthermore, the use of biodiesel in diesel engines also reduces the emission of PM, CO, polyaromatics, sulphur, UHCs and smoke [8]. This is attributed to the desirable properties of biodiesel such as higher cetane number and oxygen content as compared to fossil diesel, which improves combustion quality to reduce emission species related to incomplete combustion such as CO and UHC [9,10]. The lower sulphur and aromatics content ensure that emissions such as PAH, sulphur, smoke, UHC and PM are controlled. Additionally, biodiesel also has greater biodegradability when compared with fossil diesel [11,12]. In fact, biodiesel is expected to degrade more than 98% biologically within 3 weeks as compared to only 50% for fossil diesel. This implies that biodiesel poses lower risk of ground and surface water contamination [13,14]. Furthermore, the use of biodiesel also decreases air toxicity and cancer risks by 90% and 95%, respectively, when compared with fossil diesel [11]. These factors increase the attractiveness of biodiesel to supplant fossil diesel as the de facto fuel for diesel engines.

However, widespread adoption of biodiesel meant that more land will be required to cultivate the feedstock for the production of the fuel. This will increase the conversion of arable land usage from food to fuel production [15,16], which is likely to adversely

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affect food security [17,18]. In addition, biodiesel industry is also blamed for deforestation in some countries as natural forests are cleared for plantation purposes [19]. One method to assuage this problem is in the usage of feedstock crop with high yield per area. Hence, palm oil is a suitable feedstock for biodiesel production as it has the highest oil yield as compared to other vegetable oil, with 5000 kg oil per hectare [20]. The utilisation of palm biodiesel also produces an energy yield ratio of 3.53 which indicates a net positive energy generated, thereby ensuring its long-term viability and sustainability [21].

Although there have been numerous studies on the performance and tailpipe emissions of palm methyl ester (PME) and other biodiesel fuels in general, systematic experimental mapping of those covering the entire speed–load range of diesel engines fuelled with PME is limited. Furthermore, most of the research work is conducted on heavy-duty diesel engines. Those results are not representative of the fast-growing fleet of light-duty diesel vehicles on the road today.

To that end, the main objective of this study is to conduct an in-depth examination on the effects of speed and load on engine performance and pollutant emissions of a light-duty diesel engine when fuelled with PME. Engine-out emissions of various PME–diesel blends under a reduced emission test cycle are also evaluated to provide a realistic representation of typical on-road driving conditions. This allows the optimum blending levels to be determined. The outcome of this research work will present the required technical insights into the potential mass adoption of PME as a viable solution for the overall reduction of diesel tailpipe emissions.

2. Experimental setup

2.1. Experimental test fuel

Two fuel types, namely PME and fossil diesel were used in this experimental study. PME has near equal amount of unsaturated and saturated fatty acids in its composition, and as such is an ideal representation of commercially available biodiesel. The refined and molecularly-distilled PME used was provided by a local biodiesel producer in Malaysia. Meanwhile, a locally available commercial fossil diesel serves as the baseline fuel. Nine intermediate blends from B10 to B100 at interval of 10 vol.% were derived from the two aforementioned neat fuels. It should be noted here that present day usage of biodiesel in automotive engines is commonly limited to B20 blends due to concerns associated with its long-term usage and storage problems when neat or high level of biodiesel in fuel blends are used. However, it remains important to test high-level biodiesel blends as they can still be used with little to no modification in diesel engines if precautionary measures in storage and usage conditions are taken into account [22].

The pertinent properties of the neat fuels are summarised in Table 1. The higher cetane number when compared with fossil diesel and the presence of fuel-bound oxygen content will be favourable in promoting a more complete combustion for the fuel. However, typical to biodiesel fuels, PME suffers from a higher kinematic viscosity values that leads to poorer atomisation of the liquid fuel. PME also has a lower calorific value which increases the specific fuel consumption (SFC) as compared to fossil diesel. Nonetheless, this is expected to be partially offset due to the high density of PME, as fuel metering is volumetrically based.

2.2. Experimental installation

In this study, a single-cylinder, naturally aspirated, four-stroke direct injection (DI) 347 cc diesel test engine was used to carry out the experiments. A DI diesel engine was selected here due to its prevalence in modern day light-duty passenger vehicles [23]. The engine has an operating speed range of 1500–3500 rev/min and a rated power of 4.6 kW at 3500 rev/min. The basic specification of the test engine is shown in Table 2.

Table 1
Properties of the test fuels.

Properties	Fossil diesel	PME
C/H/O/N (wt.%)		
C	86.63	75.9
H	14.1	12.2
O	0.0	11.9
N	<1.0 (*ASTM D5291*)	0.0
Fatty acid saturation/unsaturation ratio (wt./wt.)	–	49.6/49.7
Cetane number	65.1 (*EN ISO 5165*)	67.5 (*EN ISO 5165*)
Kinematic viscosity (mm^2/s)	3.637 (*EN ISO 3104*)	4.4 (*EN ISO 3104*)
Density (kg/m^3)	837.7 (*EN ISO 12185*)	874 (*EN ISO 12185*)
Carbon residue (% m/m)	<0.100 (*EN ISO 10370*)	0.020 (*ASTM D4530*)
Calorific value (MJ/kg)	45.50 (*In-house*)	39.68 (*In-house*)

The test standards used is denoted in italic.

The test engine is coupled to an asynchronous motor mounted on an engine test stand, which forms the central pairing of the test bed. The schematic diagram of the test bed installation is illustrated in Fig. 1. Engine responses of interest such as torque, exhaust temperature, specific fuel consumption, equivalence ratio and volumetric efficiency are measured from the sensors contained within the engine test stand.

A spring-loaded governor allows engine speed measurement of up to 5000 rev/min within an accuracy range of ±2% of the measurable speed range. Torque measurement is facilitated through a suspended brake unit with a load cell. The load cell which is ratified on the OIML R60 classification has a rated output of 200 kg with a Class GP accuracy level. For the determination of the exhaust gas temperature, a K-type thermocouple with a upper measurement limit of 1000 °C and a maximum error of ±4 °C is used. A Kistler type 601A quartz pressure transducer is used to record pressure profiles. Using its quartz crystal measuring element, the in-cylinder pressure is transformed into electronic pulses for processing by the electronic indication system. The pressure transducer is capable of measuring up to 250 bars at a natural frequency of around 150 kHz, and has a sensitivity of -16 pC/bar. Fuel consumption is quantified by the way of level change in a vertical pipe at 20-s intervals, while air consumption of up to 690 L/h is gauged through a measuring nozzle. Exhaust emissions are measured using a Bosch BEA350 emissions analyser and a Bosch RTM 430 smoke opacimeter. The emissions gas analyser uses non-dispersive infrared to measure CO, CO_2 and HC, while an electro-chemical transmitter is used to measure NO. Accuracy of ±0.001 vol.%, ±0.001 vol.%, ±1 ppm vol. and ±1 ppm vol. are achieved for the measurements of CO, CO_2, HC and NO, respectively. For the smoke opacimeter, a photodiode receiver is used to measure smoke opacity up to an upper limit of 100% with an accuracy of ±0.1%. The

Table 2
Specifications of the test engine.

Parameter	Specification
Engine type	Light-duty diesel engine
Cooling type	Air-cooled
Injection type	Direct injection
Rated power	4.6 kW at 3500 rev/min
Compression ratio	22:1
Bore	80 mm
Stroke	69 mm
Connecting rod length	114.5 mm
Swept volume	347 cm^3