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Influence of second generation biodiesel on engine performance, emissions, energy and exergy parameters

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ABSTRACT

The present study compares diesel engine performance, emissions, energy and exergy parameters of three non-edible biodiesels blends and a reference diesel. The three biodiesel blends were prepared so as to keep the blend oxygen percentage at around 3.3 wt%. Considering the economy and availability, waste cooking and macadamia (*Macadamia integrifolia*) biodiesels were chosen for all the engine experiments. A commercial diesel was used as a reference fuel to compare the performance and emissions with those of the biodiesel blends. To keep the oxygen percentage of the blends approximately the same as for the reference diesel, around 30% waste cooking biodiesel was added to 70% reference diesel to make the first blend. Similarly, around 30% macadamia biodiesel was mixed with 70% reference diesel to make the second blend. In addition, 10% macadamia biodiesel and 20% waste cooking biodiesel were mixed with the 70% reference diesel to make the third blend with similar oxygen content. The macadamia blend is designated as MaD, the waste cooking blend is termed WcD, and the blend with macadamia and waste cooking biodiesel is abbreviated as MaWcD. This study aimed to investigate the influence of the fuel-oxygen on engine performance, emissions, energy and exergy parameters. A well-instrumented, 4-cylinder, 4-stroke, naturally aspirated direct injection (DI) diesel engine was used for the experiments. The engine was loaded and coupled with an eddy current dynamometer. Performance, emissions, energy and exergy parameters for the three biodiesel blends were compared with those of the reference diesel. Without significant reduction in engine performance, a significant reduction in total unburnt hydrocarbon (THC), carbon monoxide (CO), and particulate matter (PM) emissions with a penalty of increased nitrogen oxides (NOx) emissions were realised with all three biodiesel blends.

1. Introduction

Studies are available on assessing the influence of non-edible biodiesels on engine performance and emissions [1–4]. Notably, Ong et al. [2] performed engine experiments using biodiesel–diesel blends of 10%, 20% and 30% for *Ceiba pentandra, Jatropha curcas*, and *Calophyllum inophyllum* (beauty leaf) to examine engine performance and emission characteristics. They reported better results for the 10% blends. Compared to commercial diesel fuel, the biodiesel blend drops BP, torque and BTE, and increases BSFC, which is due to the low heating value of biodiesel [2,5]. Chandra Sekhar, Karuppasamy [6] produced biodiesel from *Pithecellobium dulce* seed oil and investigated its influence on engine performance and emissions. Compared to diesel, lower in-cylinder pressure, rate of heat release and exhaust temperature were observed with the *Pithecellobium dulce* seed oil methyl ester blends; however, brake specific fuel consumption was higher with them. Concerning the emissions, the THC, CO, and NOx were reduced, however smoke emissions and CO_2 were increased with the biodiesel blends.

It is well-known that there are three types of NOx formation mechanisms. Those are thermal NOx, fuel NOx and prompt NOx [7]. Thermal NOx, a major contributer to total NOx emissions, is mainly due to high flame temperature and is generally formed at higher than 1100 °C. Exhaust gas recirculation technique is an established method to reduce the flame temperature and hence to reduce thermal NOx emissions. CH_2, and CH and are the major contributors to prompt NOx formation. Prompt NOx usually increases as equivalence ratio increases, reaches a maximum and then drops due to lack of oxygen [7]. Fuel NOx is formed when nitrogen in the fuel reacts with excess oxygen during the combustion process. The growth of intermediate nitrogen species including NH_3, NH, and HCN and their oxidation leads to the fuel NOx formation [7]. Governing equations for various NOx formation mechanisms can be found in [7].

Generally, biodiesel blends increase NOx emissions compared to

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diesel; however, they significantly decrease other emissions including PM, CO, and HC [5,8–10]. It was reported that the exhaust emissions of THC, CO and PM are lower on average by 67%, 48% and 47%, respectively, when using biodiesel compared to diesel fuel [11].

Thermodynamic models are the tools for engine performance analysis. Although the First Law of Thermodynamics is a recognised method of predicting engine performance [12], it often fails to provide the best understanding of the engine's operation. With the aim of evaluating the inefficiencies associated with the different processes, analysis using the Second Law of Thermodynamics needs to be applied [13]. One of the key concepts of such an analysis is "availability or exergy" that specifies the potential to produce useful work. An exhaustive search reveals a few studies are available on exergy analysis for internal combustion engines. Madheshiya and Vedrtnam [14] conducted experiments in a 4-stroke diesel engine with different biodiesel blends. They assessed exergetic performance parameters and reported similar results. Meisami and Ajam [15] performed engine experiments with various biodiesel blends in a 4 cylinder turbocharged diesel engine. The evaluated both energy and exergy parameters using the biodiesel blends and realised higher destruction efficiency with the biodiesels. Aghbashlo, Tabatabaei [16] did an exergy analysis for a diesel engine using 5% biodiesel blends with different amounts of expanded polystyrene. They realised that the exergy parameters depend on engine load and speed. They also reported that the exergy efficiency and sustainability index decreases as speed increases.

In this study, the influence of waste cooking and macadamia biodiesels and diesel blends on engine performance and emissions characteristics are investigated first, and then energy rate (quantity of energy) and exergy rate (quality of energy) are determined keeping the oxygen percentage of blends at approximately 3.3%.

2. Materials and methods

2.1. Experimental procedure

Two non-edible biodiesels including waste cooking and macadamia biodiesels were chosen for the experiments. The target of this investigation was to investigate the influence of fuel oxygen on different performance, emission, energy and exergy parameters. There were three biodiesel blends prepared for the engine experiments. A reference diesel fuel was also used for comparison. Some key fuel properties are listed in Table 3. The details of engine performance, and exergy parameters were discussed in the paper.

A well-equipped 4-cylinder, 4-stroke naturally aspirated diesel engine (Kubota, model V3300) was used for all experiments. The experimental and instrumentation arrangements are shown in Fig. 1. The key specifications of the engine are depicted in Table 1. For measuring the different gas components (Table 2), an exhaust gas analyser (Model CODA 5) was used to measure the exhaust emissions including THC, CO, O_2, NOx, and CO_2 emissions. For the diesel particulate matter (PM), a particulate meter (MAHA MPM-4M) was used in this investigation. The engine was run at four different loads of 25%, 50%, 75% and 100% at a rotational speed of 2500 rpm. The reason for choosing this speed was that it is close to the rated power speed. The in-cylinder pressure data was recorded with a pressure transducer (Optrand model H32218-GPA). The engine was first warmed up with the reference diesel fuel for about 30 min. The measurements were started once the oil temperature reached 80 °C. Separate fuel tanks for the three biodiesel blends were used in the experiments. For the different biodiesel blends and the reference diesel, the maximum load was determined when the throttle was fully open (wide open throttle position) for 2500 rpm. The load at this condition was considered as 100%. Based on this 100% load, other loads were calculated for all four fuels [19]. Collecting the performance and emissions data of each fuel was repeated thrice and the mean values were used.

2.2. Equations for calculating different performance, combustion, energy and exergy parameters

2.2.1. Fuel exergy rate

The specific chemical exergy of a fuel can be estimated with Eq. (1) [20].

$$\text{Specific chemical exergy} = \left[1.0401 + 0.1728\frac{h}{c} + 0.0432\frac{o}{c} + 0.2169\frac{s}{c}\left(1-2.0628\frac{h}{c}\right)\right]LHV \quad (1)$$

where c, h, o, and s are the mass fractions of carbon (C), hydrogen (H), oxygen (O) and sulphur (S) respectively.

The fuel exergy rate, which can also be termed the input exergy rate, is then calculated using Eq. (2).

$$\text{Fuel exergy rate} = \dot{m}_f \times \text{specific chemical exergy} \quad (2)$$

2.2.2. Fuel energy rate

The fuel energy rate is calculated using Eq. (3).

$$\text{Fuel energy rate} = \dot{m}_f \times |LHV| \quad (3)$$

where $\dot{m}_f$ is the mass flow rate of fuel. The different values of C, H, and O are given in Table 3. Fuel sulphur was not taken into consideration, as the reference diesel was an ultra-low sulphur fuel and biodiesels have a negligible amount of fuel sulphur.

2.2.3. Brake mean effective pressure (BMEP)

The calculation of BMEP is shown in Eq. (4).

$$BMEP = \frac{\text{Brake power}}{lank/2} \quad (4)$$

where a is the in-cylinder area; l is the stroke length; n is the engine rotational speed; k is the number of cylinders; The numeric 2 applies to a 4-stroke engine.

2.2.4. Brake specific energy consumption (BSEC)

The BSEC was estimated using Eq. (5) which indicates that the BSEC is directly proportional to the fuel heating value and the fuel mass flow rate, while being inversely proportional to the brake power.

$$BSEC = \frac{\text{Fuel heating value} \times \dot{m}_f}{\text{Brake power}} \quad (5)$$

where $\dot{m}_f$ is the mass flow rate of fuel.

2.2.5. Fuel conversion efficiency

The fuel conversion efficiency was calculated with Eq. (6).

$$\text{Fuel conversion efficiency} = \frac{\text{Brake power}}{\text{Fuel heating value} \times \dot{m}_f} \quad (6)$$

2.2.6. Fuel energy rate

The exergetic efficiency is also termed as second law efficiency and is calculated with Eq. (7).

$$\text{Exergetic efficiency} = \frac{\text{Output egergy}}{\text{Fuel exergy}} \quad (7)$$

2.2.7. Rate of heat release (RoHR)

The computation of RoHR was done using Eqs. (8) and (9) [21].

$$\frac{dP}{d\theta} = -\gamma\frac{P}{V}\frac{dV}{d\theta} + \frac{\gamma-1}{V}\left(\frac{dQ}{d\theta}\right) \quad (8)$$

Upon simplication, the RoHR was calculated by the following equation: