Comparison of the performance and emissions of different biodiesel blends against petroleum diesel

P. McCarthy, M.G. Rasul* and S. Moazzem
Central Queensland University, Rockhampton, Queensland 4702, Australia

Abstract

Biodiesel, an alternative fuel of petroleum diesel, is mainly used to reduce the environmental impact of emissions without modifying engines. This study compares the performance and emissions characteristics of different biodiesel blends with petroleum diesel using an internal combustion engine (Kubota V3300) and following ISO 8178 standards. Two types of biodiesel, type A (80% tallow and 20% canola oil methyl ester) and type B (70% chicken tallow and 30% waste cooking oil methyl ester), were tested in this study. It was found that the performance (mainly torque and brake power) of both biodiesel fuels reduces with increasing blend ratio which can be attributed to lower energy content of biodiesel. Specific fuel consumption increases for both biodiesels compared with diesel fuel, as expected. Some of the greenhouse gas emissions were found to be higher than petroleum diesel, whereas some were lower. Overall, Biodiesel A was found to produce lower emissions across the board compared with diesel and Biodiesel B.

Keywords: biodiesel; internal combustion engine; engine performance and emissions

*Corresponding author:
m.rasul@cqu.edu.au

Received 22 October 2010; revised 18 May 2011; accepted 27 May 2011

1 INTRODUCTION

It is well known that petroleum diesels are the major source of air pollutions that create an adverse impact on human health and overall greenhouse gases. Biodiesel has some great benefits over petroleum diesel, such as it produces 4.5 units of energy against every unit of fossil energy [1, 2] and also it has some environment-friendly properties such as it is non-toxic, biodegradable and safer to breathe [3]. Biodiesel is also a clean-burning and stable fuel [3]. Properties of biodiesel such as oxygen content, cetane number, viscosity, density and heat value are greatly dependent on the sources (soybean, rapeseed or animal fats) of biodiesel [4, 5]. Engine performance and emissions depend on the properties of biodiesels. Biodiesel is a highly oxygenated fuel that can improve combustion efficiency and can reduce unburnt hydrocarbons (HCs), carbon dioxide (CO₂), carbon monoxide (CO), sulphur dioxide (SO₂), nitric oxide (NOₓ) and polycyclic aromatic HC emissions. However, brake-specific fuel consumption slightly increases [6].

Popularity of biodiesel as renewable sources of alternative fuel of petroleum diesel is growing quickly due to increased environmental awareness and the rising price of diesel. It is an earth-friendly choice of consumers that already occupies a great volume of the world’s fuel sector due to its clean emission characteristics.

Developments of biodiesel fuels in many countries are driven by the necessity to reduce the greenhouse gas emissions which is the major issue for today’s world, and the scarcity of the source of petroleum diesel also enhances the development and production of biodiesel fuel around the world. Biodiesel is generally produced from vegetable oils or animal fats through a chemical process known as transesterification process.

Vegetable oil was first used to run an engine by Rudolf Diesel (1858–1913) who developed the first engine. But sometimes, vegetable oils create adverse effects on engine components which may be due to their different volatility and molecular structure from diesel fuel as well as high viscosity compared with diesel fuel [4, 5, 7]. Currently, this problem is being eliminated by applying different chemical processes such as transesterification, supercritical, catalyst-free process etc., on vegetable oils to convert into biodiesel.

This paper aims to investigate the engine performances (power, torque, fuel consumption) and emissions (unburnt HCs, carbon dioxide, carbon monoxide and nitric oxide) of a diesel engine using two different biodiesels. Two different sources of biodiesel, type A [80% tallow (beef, pork and sheep) and 20% canola oil methyl ester] and type B (70%...
chicken tallow and 30% waste cooking oil methyl ester), were used for the experimentation in this study. Fuel types such as B5, B10, B20, B50 and B100 are analysed and discussed.

2 THEORETICAL CONSIDERATION

Performances of a compression ignition (CI) engine are tested by running them at different loads and speeds and taking sufficient data for performance criteria. Engine performance depends on the testing conditions and the form in which the engine is tested such as fully or partly loaded. The power output changes with the change of pressure, temperature and humidity [8]. Artificially improving the volumetric efficiency, it is affected by various factors such as mixture strength, compression ratio, specific enthalpy of vaporization of the fuel, heating of the induced charge, cylinder temperature, valve timing, induction and port design and the atmospheric conditions [8].

Volumetric efficiency with normal aspiration is above 80% and it is affected by various factors such as mixture strength, compression ratio, specific enthalpy of vaporization of the fuel, heating of the induced charge, cylinder temperature, valve timing, induction and port design and the atmospheric conditions [8].

The initial conditions for compressions (when the piston is at bottom dead centre) can be written as,

\[ V_i = V_{vol} \times V \quad \text{and} \quad p_0 = p_0 \times \eta_{vol} \]

When the manifold air is compressed,

\[ V_i = V_{comp} \quad \text{and} \quad p_0 = p_i \times \eta_{vol} \]

where \( p_i \) is the indicated power (in kW) and \( p_0 \) the output power (in kW).

3 EXPERIMENTAL CONSIDERATION

In this study, Kubota V3300 indirect injection, four cylinder, naturally aspirated, CI engine as shown in Figure 1, was used to investigate the performance and emissions of test fuels. The rated power output is 50.7 kW at 2600 rpm, and the rated torque is 230 Nm at 1400 rpm. Table 1 shows the specifications of Kubota V33. The three main parameters that characterize the performance of a diesel engine are brake power, torque and specific fuel consumption which have been investigated in this experiment. Specific fuel consumption is defined by the mass flow rate of fuel consumed per unit power output. The brake power and torque are evaluated by a dynamometer. Specific fuel consumption is evaluated by measuring the flow rate of fuel being supplied to the engine with a fuel flow meter. In the case of an absorption dynamometer, the torque is obtained by...
the net load at a known radius, given by

\[ T(\text{Torque}) = WR \]  

where \( W \) is the net load and \( R \) the radius [10].

Brake power (bp) = \( 2\pi NT \)  

Mechanical efficiency of the CI engine is given by,

\[ \mu_M = \frac{\text{bp}}{\text{ip}} \]  

The exhaust gas analyser (EGA) used for measuring exhaust gas emissions was an Andros 6241A, 5 gas analyser. This EGA takes instantaneous readings of a sample of exhaust gas taken from the exhaust stream. It measures oxygen, carbon dioxide, carbon monoxide and HCs using a non-dispersive infrared sensor. This model also measures nitric oxide, using an electrochemical sensor.

The biodiesel–diesel blends that referred to as B5, B20, B50 and B100 were used in this study, where the percentage ratios of biodiesels are 5%, 20%, 50% and 100%, respectively. Two types of biodiesels were used in this study to blend with petroleum diesel, type A [80% tallow (beef, pork and sheep) and 20% canola oil methyl ester] and type B (70% chicken tallow and 30% waste).

ISO 8178 test procedure was used in this study which is an eight-mode steady-state test procedure that comprises three engine speeds, rated speed, intermediate speed and low idle for testing. The minimum test mode length of each mode is 10 min and emissions are measured in the last 3 min of each mode. The engine is preconditioned by warming up the engine at its rated power for 40 min before each test cycle and minimum 50 data were taken for each mode in each test cycle, and three cycles are run per test fuel and then average. Experiments were done at both 2600 and 1400 rpm.

4 RESULTS AND DISCUSSION

Fuel consumption of biodiesel is expected to be slightly higher than petroleum as density of the biodiesels is higher than petroleum diesel [11]. Sources of biodiesel greatly influence the engine performance, e.g. the engine fuelled with palm oil biodiesel is more efficient than biodiesel produced from tallow and canola oil [12]. Biodiesel is likely to produce less power with high fuel consumption than diesel as the gross calorific value (energy content) of biodiesel is lower than petroleum diesel. Blends of biodiesel with petroleum fuel are widely used in the diesel engine [13]. High viscosity of the fuels causes fuel flow and ignition problems in unmodified CI engines and also decreases the power output [11, 14]. The lubricity and oxidative stability of the animal fat-based biodiesels are better than soy-based biodiesel [15, 16]. The composition of animal fatty acid methyl esters is different from vegetable fatty acid methyl (ethyl) esters.

The results of performances and emissions of biodiesels tested in this study (Biodiesels A and B) compared with diesel are presented and discussed below.

4.1 Torque and power

Figure 2 shows the torque as a function of diesel and biodiesel blends for both Biodiesels A and B using modes 1 and 5 of the ISO 8178 test procedure. Mode 1 corresponds to the rated speed of the engine (2600 rpm) at 100% throttle, and mode 5 corresponds to the intermediate speed of the engine (1560 rpm) at 100% throttle. These two modes are the only
ones that give a good indication of the differences in torque when using biodiesel, as the other modes require the torque to be set to a value (therefore reducing the throttle from 100%) which is the same for all test fuels. It can be seen from Figure 2 that the output torque decreases with increasing blend ratio for both biodiesels. The percentage decrease for both biodiesels at these modes is in the range of 4–5%. A decrease in this magnitude is to be expected, due to the lower energy content of biodiesel. The decrease in output torque at these two modes also affects the power output of the engine, since torque and power are directly proportional when the engine speed is fixed. As a result, the power output will also decrease by 4–5%. A decrease in both power and torque is due to their lower energy content of biodiesel.

### 4.2 Specific fuel consumption

Figure 3 compares the specific fuel consumption for the two biodiesels over the ISO 8178 test procedure. Even though this test procedure is designed to evaluate exhaust emissions, it can also be used in the same way to measure fuel consumption. During testing, the fuel flow rate at each mode was measured, and by using the weighting factors designated in the test procedure, a value for fuel consumption over the duration of the test was found, and averaged over the three tests for each fuel. Since the test procedure requires set values of torque and rpm, fuel consumption should be higher for a fuel with lower energy content.

From Figure 3, it can be seen that fuel consumption increases with blend ratio for both Biodiesels A and B. For Biodiesel A, the fuel consumption is 7% higher than diesel and for Biodiesel B, it is +10% higher which indicates that Biodiesel B has lower energy content than Biodiesel A and both biodiesels have lower energy content than diesel.

### 4.3 Exhaust emissions

Figure 4 compares the NO\textsubscript{x} emissions for Biodiesel A, Biodiesel B and diesel. Biodiesel A nitric oxide emissions show a decreasing trend with increasing blend ratio, whereas Biodiesel B emissions increase with the blend ratio. NO\textsubscript{x} emissions can increase or decrease depending on a number of factors such as biodiesel type, engine type and test procedure used. The US EPA reports a 10% increase in NO\textsubscript{x} emissions for B100 when compared with diesel.

Figure 5 shows the carbon monoxide emissions for Biodiesels A and B over the ISO 8178 test procedure. Both biodiesels displayed a significant decrease in CO emissions with increasing blend ratio. For Biodiesel A, the decrease is \sim 55% and for Biodiesel B, the decrease is \sim 30%. This decrease fairly agrees with US EPA [4] who reported 51% decrease in CO emissions for biodiesel. This decrease could be attributed to the biodiesels having higher oxygen content than diesel which can result in a more complete combustion, leading to less CO in the exhaust stream.

The HC emission results for the biodiesels are shown in Figure 6. It can be seen that both Biodiesels A and B show an increase in HC emissions with increasing blend ratio. Conversely, the US EPA reports that HC should decrease with
increasing blend ratio. It should be noted that the HCs measured during testing were very low (~0.002%). This brings into question the validity of these results, since other studies have found significantly higher levels of HCs in diesel exhaust emissions. These low readings could be attributed to a number of factors, one being that the EGA is optimized for measuring petrol engine exhaust emissions, not diesel. Petrol engine emissions contain different HCs to diesel engines, and higher concentrations of HC. If diesel/biodiesel HCs were to be measured accurately, a flame ionization detector would need to be used instead of the infrared sensor that was used for this testing, but this equipment is extremely expensive. Another explanation for inaccurate HC readings is that HC drift was occurring. Drift occurs when the emissions sample point is too far down the exhaust stream, which gives the HCs a chance to break down into other compounds such as carbon dioxide and water vapour. Since the sample point is ~3 m down the exhaust stream on the test rig, it is possible that this is sufficient distance for some of the HCs to break down; therefore, a reduced amount is actually being measured.

Figure 7 shows the carbon dioxide emissions for the biodiesels over the ISO 8178 test procedure. It can be seen that both biodiesels display an increase in CO2 emissions with increasing blend ratios, although a decrease in CO2 emissions was expected as CO emissions presented in Figure 5. For Biodiesel A, the increase is ~6% and for Biodiesel B, the increase is ~18% compared with diesel. It is to be noted that CO2 is a non-regulated emission (i.e. not limited), but is frequently measured when analysing exhaust gas emissions as it gives valuable clues on fuel consumption in dynamometer tests [17]. Studies have shown that biodiesel can decrease CO emissions up to 51%, whereas it can increase or decrease CO2 emissions, with the percentage change ranging from ~7% to +7% depending on the type of biodiesels [18, 19]. In the current study, Biodiesel A clearly agrees with the literature findings both in terms of CO and CO2 emissions; however, a higher increase in CO2 emissions was found for Biodiesel B compared with literature findings. This difference can be considered as not very significant, as CO2 emissions are not regulated. However, the specific reason for increase in CO2 emission for both the biodiesels studied in this study (i.e. Biodiesels A and B) needs further investigation.

4.4 Summary of discussion
The summary of discussion based on the experimental findings is outlined below:

- Lower energy content of biodiesel results in the lower performance (torque and power). It shows a decrease in both power and torque for biodiesel fuels.
- Emissions of HC and CO2 from both biodiesels increase with increasing the amount of biodiesel in their blend, whereas CO emission decreases with increasing amount of biodiesel in the blend.
- Fuel consumption for Biodiesel B is higher than Biodiesel A, and Biodiesel B has lower energy content than Biodiesel A. This indicates that fuel consumption is higher for fuel with lower energy content.
- Biodiesel A has lower exhaust emissions and better performance compared with Biodiesel B.
- NOx emission depends on a number of factors such as biodiesel type, engine type and test procedure used.
In this experiment, Biodiesel A shows a decreasing trend with increasing blend ratio whereas Biodiesel B shows increasing trend with increasing blend ratio for NO\textsubscript{x} emission.

- Biodiesels having higher oxygen content can lead to less CO emissions with increasing blend ratio due to complete combustion in the diesel engine.
- A diesel engine fuelled with biodiesel can make complete combustion due to the presence of oxygen content in the molecule of biodiesel.
- Fuel consumption of biodiesel is expected to be higher when engine fuelled with higher density biodiesel.
- An engine fuelled with biodiesel containing higher cetane number and higher lubricity is more efficient.
- Biodiesel with higher gross calorific value (energy content) produces higher power.
- High viscosity of the biodiesel causes fuel flow and ignition problems in engines and decreases in power output.

5 CONCLUSIONS

The results of this study indicated that biodiesel is a more environmental-friendly option than petroleum diesel based on the reductions in CO and NO\textsubscript{x} in the tailpipe emissions. This comes at the cost of performance, though biodiesel has lower energy content than petroleum diesel. Biodiesel A (the 80% beef, pork and sheep tallow and 20% waste cooking oil methyl ester) was found to have lower exhaust emissions across the board compared with Biodiesel B (70% chicken tallow and 30% waste cooking oil methyl ester). Without knowing more about the exact fuel properties of these two fuels, such as ultimate analysis, it was difficult to draw any definitive conclusions about why emissions were higher for biodiesels. It is recommended that a follow-up study should be completed to further investigate the fuel properties of Biodiesels A and B in order to determine how the differences in chemical properties affect performance and emissions. Once these fuel properties data are obtained, it could be inputted into an appropriate engine simulation programme to analyse theoretical emissions data. If the model was found to be accurate enough, these theoretical data could be compared against the practical data found in this study, which would provide more insight into the performance and emissions of biodiesel fuels.

REFERENCES