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The effect of Butanol-Acetone Mixture-Cottonseed Biodiesel Blend on Spray Characteristics, Engine Performance and Emissions in Diesel Engine

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Abstract

Increasing energy demands and more stringent legislation relating to pollutants such as nitrogen oxide (NO_x) and particulate matter (PM) from mineral fuels used in diesel engines have encouraged the use of biodiesel. Biodiesel fuels produced from non-edible oils have properties comparable to diesel fuel, which make them promising alternative fuels. However, there are some drawbacks associated with biodiesel as fuel for compression-ignition (CI) engines such as high viscosity and higher NO_x emissions. Using an alcohol butanol-acetone (BA) or acetone-butanol-ethanol (ABE) mixture is one solution to improve blend efficiency and also to lower NO_x emissions. The aim of this paper is to investigate the impact of a BA or ABE mixture blended with cottonseed biodiesel on spray characteristics, engine performance (in-cylinder pressure, brake power (BP) and specific fuel consumption (SFC)) and emission levels (NO_x and carbon monoxide (CO)). The results demonstrated that BA and ABE decreased biodiesel viscosity and resulted in improved spray characteristics. BP was reduced while SFC was increased. The peak in-cylinder pressure was comparable at a lower engine speed while being slightly lower at 2000 rpm. The maximum reduction in NO_x and CO was shown to be from 10BA90Bd by 13.84% and 41.5% respectively at 2000 rpm.

1 Introduction

Significant energy demands from population growth together with environmental concerns have encouraged researchers to look for renewable energy resources. There are a number of substitute fuels produced from different edible and non-edible resources. Biodiesel is methyl or ethyl ester or fatty acid made from vegetable oils and animal fat. Cottonseed is one non-edible resource of biodiesel production. There are molecular similarities between biodiesel and conventional diesel fuel. Therefore biodiesel can be used directly or as an additive for conventional fuels, increasing the chance of replacing fossil fuels in the near future. However, current limitations of using biodiesel as an alternative fuel for CI engines include: (1) high density and viscosity due to large molecular weight and complex chemical structure [1], which causes obstacles in completing fuel atomisation and combustion [2]; (2) lower heating value due to the oxygen content which produces less engine power [3] and (3) production of higher NO_x emissions (which increases health problems) due to high combustion temperature [4]. There are many ways used to solve these issues including: (1) micro-emulsion (biodiesel washing with water and blending with surfactants) (however, some experimental studies have found that micro-emulsion can lead to negative effects in injection systems due to low lubricity and wear corrosion) [5, 6]; and (2) use of an exhaust gas recirculation (EGR) system. Some experiments have demonstrated an increase in PM and these techniques require engine modification at extra cost. Therefore, using alcohol as an additive to improve biodiesel properties and combustion efficiency is a good option. Bio-alcohols derived through biochemical processes from different biomass resources have a high oxygen content, which helps to complete the combustion [7].

In particular, ethanol and methanol with biodiesel have been extensively investigated [8,9]. However, some studies revealed some disadvantages of ethanol and methanol used as blends for use in diesel engines. Therefore, researchers have suggested the use of butanol as a suitable blend for diesel engines [10]. Butanol presents comparable fuel properties to conventional diesel and these benefits can be utilised to improve the fuel efficiency and can contribute to providing power comparable to regular diesel fuel while producing less emissions [11]. However, the cost of butanol production is the main issue of using it as fuel in internal combustion (IC) engines. Because of the high recovery and purification costs, other fermentation products such as ABE and BA mixtures (the intermediate outcome during the production of butanol) have been proposed as an additive blend. This provides the potential to reduce NO_x and CO emissions in CI engines. ABE is produced in the typical ratio of ABE (3:6:1) [12].

A study by Li et al. [13] found that it was possible to produce a mixture of butanol and acetone (2.9:1) with no ethanol from the fermentation process when cassava was used as substrate in the fermentation. To our knowledge, BA as an additive to biodiesel has not been investigated. The aim of this paper is to investigate the impact of a BA or ABE mixture on cottonseed

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biodiesel characteristics and compare them to conventional diesel as a baseline fuel regarding spray characteristics, engine performance and emission levels.

2 Methodology

This Normal butanol (nB) and acetone (A) were used at 99.8% analytical grade. Ethanol (E) was used at 100% analytical grade. A neat cottonseed biodiesel (Bd) was obtained from Queensland University of Technology (QUT). The cottonseed methyl ester fuel was prepared from cottonseed oil via transesterification. Diesel was obtained from a local petrol station in Toowoomba, Australia as a baseline. A BA mixture was prepared with a ratio of 2.9:1 (B:A) by volume and an ABE mixture with a ratio of 3:6:1, which was used to simulate the intermediate fermentation production. Once this was completed, different volumetric blends with neat cottonseed biodiesel were formed: 10% BA or 10% ABE blended with 90% cottonseed biodiesel, referred to as 10BA90Bd and 10ABE90Bd respectively. Table 1shows properties of the fuel blends.

Properties	A	E	nB	Bd	D
Density (kg/L)	0.971	0.795	0.810	0.85	0.85
Viscosity (mm^2/s)	0.35	1.08	2.22	4.4	1.9-4.1
Calorific value (MJ/kg)	29.6	26.8	33.1	36.8	42.8
Surface tension (mN/m)	22.6		24.2	32.4	23.8

Table 1. Fuel properties.

The spray experimental test was carried out on a constant volume vessel (CVV) at atmospheric pressure. An air-driven high-pressure fuel pump was used in the fuel injection system using a solenoid Bosch-type injector with six holes and two different injection pressures (300 bar and 500 bar). A Photron Charge-Coupled Device (CCD) camera was used to capture the spray blend images. The camera has a resolution of 1024×1024 pixels. An LED light was used for illuminating the fuel spray on each window to ensure constant background light for the camera.

The engine test was conducted using a single-cylinder, four-stroke, water-cooled, direct injection (DI) diesel engine. An electrical dynamometer connected to the engine was used to control the load. The crank angles were measured using a crank angle encoder set up on the shaft of the engine. A Kistler 6052C pressure transducer (CT400.17) and charge amplifier connected to a data acquisition system with software (CT 400.09) were used to record cylinder pressure values at one crank angle for 50 cycles each test. The exhaust gas emission was analysed using a Coda gas analyser to measure NO_x, and CO. The test was carried out at a compression ratio of 19:1 with three engine speeds (1400, 2000 and 2600 rpm) at full load. The test began at least 20 minutes before recording commenced. The experiments were carried out in triplicate to reduce the experimental error.

3. Result and Discussion

3.1 Spray Characteristics

Before testing biodiesel blends in an engine, spray visualisation should be understood because fuel spray characteristics result in an air-fuel mixing rate which has a direct impact on the engine performance and emission levels. Spray images of neat diesel (D), neat biodiesel (Bd), 10BA90Bd and 10ABE90Bd blends are illustrated at two injection pressures 300 bar and 500 bar in Fig. 1 and Fig. 2. The main drawback of biodiesel is its higher viscosity and higher surface tension (Table 1) which resulted in a reduction of the Weber number and injection velocity respectively [14, 15]. It also led to an increase in droplet size compared to neat diesel [15]. In addition, the higher viscosity of biodiesel required a high injection pressure to reduce the friction force contact between the nozzle wall and the fuels. The high jet penetration and poor atomisation resulted in an insufficient reaction rate which leads to reduced engine power and increased fuel consumption. Adding ABE or BA mixtures can improve spray penetration due to the benefits of its properties to decrease viscosity and surface tension which results in improving air-fuel mixing.

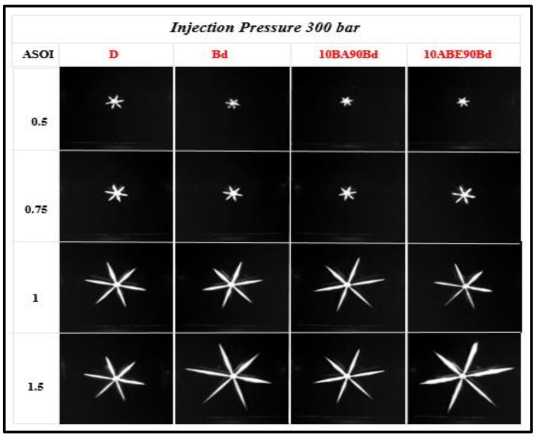


Figure 1. Spray images of different test.

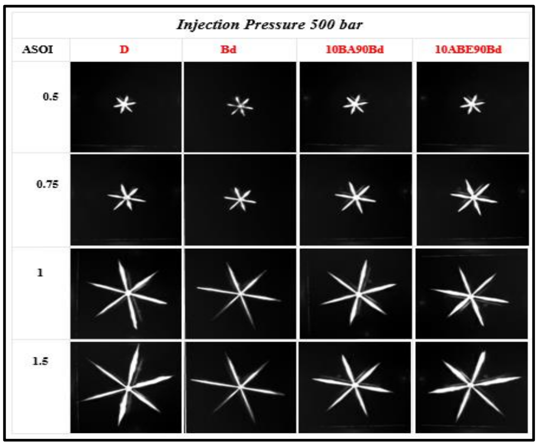


Figure 2. Spray images of different test.

3.2 Engine Performance

3.2.1 In-Cylinder Pressure

Figure 3 presents the relationship between the peak in-cylinder pressure trace and the crank angle of the test fuels at 1400 and 2000 rpm. It can be seen in Fig. 3 that the peak in-cylinder pressure of the BA/ABE-biodiesel blends is comparable with neat diesel at 1400 rpm. In contrast, the peak in-cylinder pressure of 10BA90Bd and 10ABE90Bd was slightly lower compared to that of neat diesel at 2000 rpm. This result was in an agreement with Nabi et al [16] who noticed that the peak in-cylinder pressure of biodiesel was 12% less than diesel.

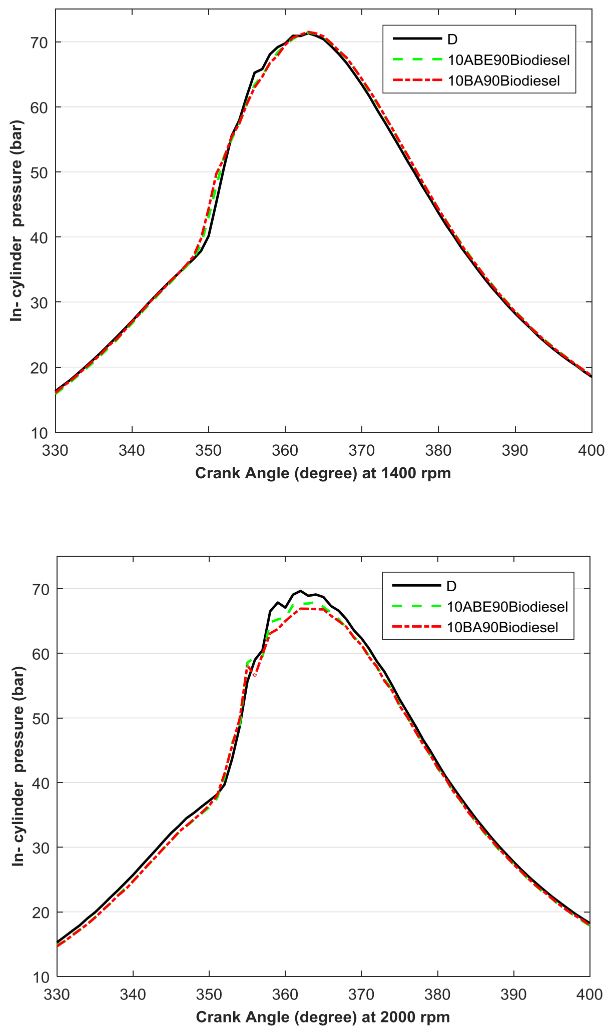


Figure 3. In-cylinder pressure of test fuels (a) 1400 rpm and (b) 2000 rpm.

3.2.2 Brake Power (BP) and Specific Fuel Consumption (SFC)

Figure 4 shows the variation of BP and SFC with the engine speed of the test fuels. It is observed that BP was reduced, while SFC was increased with both fuel blends compared to that of neat diesel due to the low calorific value of the blends (Table 1).

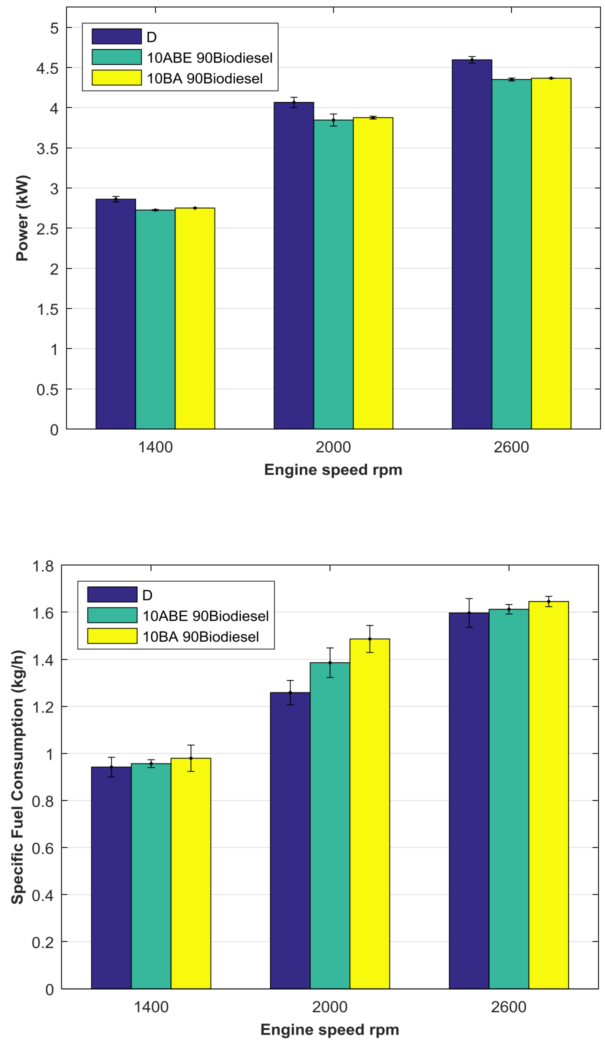
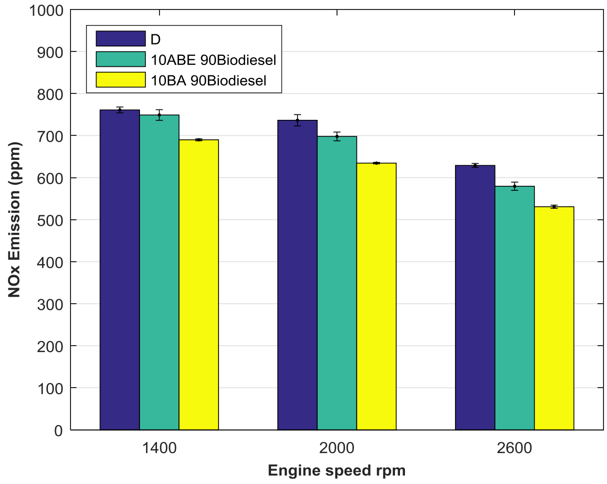


Figure 4. BP and SFC of test fuels.

3.2.3 NO_x and CO Emissions

Figure 5 presents the NO_x and CO emissions of the test fuels at various engine speeds. All BA/ABE-biodiesel blends showed a decrease in NO_x and CO emissions compared to that of neat diesel. The maximum reduction in NO_x and CO was shown for 10BA90Bd by 13.84% and 41.5% respectively at 2000 rpm engine speed. This reduction is due to the BA or ABE mixture having a high oxygen content, which results in decreased exhaust gas temperature (EGT). This reduction in EGT results in reduced NO_x and CO emissions.



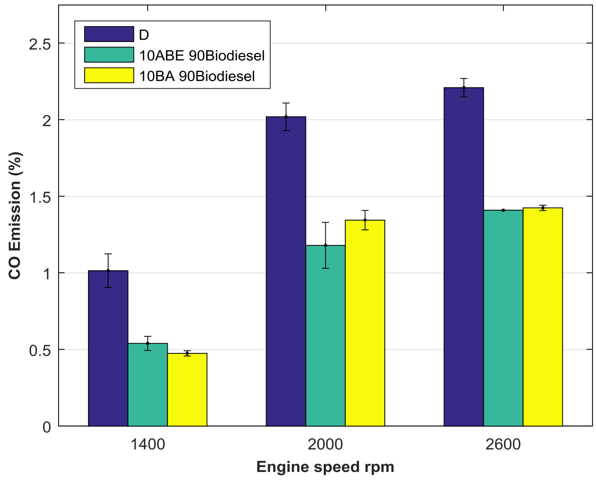


Figure 5. NO_x and CO emissions of test fuels

4 Conclusions

The experimental work has concluded some significant results for the test blends. The results are as follows:

- BA or ABE can enhance the spray characteristics of biodiesel, which results in improved air-fuel mixing.
- The peak in-cylinder pressure of 10BA90Bd was comparable to neat diesel at a lower engine speed.
- All ABE/BA-biodiesel blends showed a decrease in NO_x and CO emissions at all engine speeds. The maximum reduction in NO_x and CO emissions was for 10BA90Bd by 13.84% and 41.5% respectively at 2000 rpm compared to neat diesel.

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