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Comparative study of spray characteristics of butanol, acetone-butanol-ethanol, butanol-acetone/diesel blends.

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Abstract

Butanol is widely investigated as a renewable biofuel additive in Compression-Ignition (CI) engines due to its ability to improve diesel fuel properties and reduce emission levels. Because Acetone-butanol-ethanol (ABE) and butanol-acetone (BA) are intermediate mixtures in bio-butanol production, they present cost benefits compared to butanol production by reducing energy consumption and the number of recovery processes. This paper evaluates and compares the effect of using butanol (B), BA and ABE additives with diesel (D) on macroscopic spray characteristics. Spray tests were carried out in a constant volume vessel (CVV) under different injection conditions. A high-speed camera was used to record spray images. Macroscopic spray characteristics including spray penetration, spray cone angle and spray volume were measured. The experimental results showed that spray penetration (S) was increased as a result of addition of all alcohols to diesel fuel as well as of increased injection pressure; spray cone angle (θ) was slightly widened while it was slightly narrowed as a consequence of increase fuel injection. The spray volume of the alcohol-diesel blends showed a higher value compared to that of neat diesel due to high spray penetration length. Spray penetration and spray volume of BA-diesel blend were higher compared to ABE-diesel and B-diesel blends.

Butanol-acetone mixture; Acetone-Butanol-Ethanol mixture; spray visualization.

1. Introduction

The pollution emitted from diesel engines such as carbon monoxide and nitric oxide causes serious health risks to human beings. Reducing carbon emissions have become a necessary goal to reduce global warming [1, 2, 3]. Optimising the combustion process in internal combustion engine is necessary to reduce both the fuel consumption and the pollutant emission levels. Compression ignition (CI) engines' performance and emissions are highly impacted by fuel spray techniques [4, 5]. Hence, it is important to understand the spray behaviour and atomisation characteristics of these fuels as individuals and mixtures especially when using these fuels directly in non-modified or slightly modified diesel engines [6, 7]. One way to reduce the reliance on fossil fuel is to blend it with additives. Butanol is a potential renewable resource of alcohol which can be blended with diesel. Butanol has some advantages compared to ethanol, such as being stable with diesel at any ratio without any phase separation. being less corrosive, having a higher flash point which means it is a safer option for storage and distribution, having a higher energy content and lower vapour pressure and high burning velocity which reduces emissions (such as soot, smoke, NO_x and CO) [8]. However, the cost of butanol production is the major issue of limiting its use as a fuel in internal combustion (IC) engines. It is preferable to use ABE or BA as a mixture because butanol is the most abundant component in the ABE and BA mixture and the purification cost would be minimised as a consequence of reduce energy consumption and recovery processes[1].

Algayyim et al. [3] studied the macroscopic spray characteristics of butanol-acetone mixture (BA) as additive for diesel fuel under two injection pressures 300 bar and 500 bar. Two butanol types (normal butanol and iso-butanol: iso-BA and n-BA) were investigated as components in a BA mixture. The experimental result showed that all BA mixture enhanced spray penetration. Spray penetration of n-BA-diesel was slightly higher than that of iso-BA-diesel blend. Therefore, an ABE or BA mixture can enhance the evaporation rate which improves the combustion rate. Liu et al. [9] used an optical CVV to compare the effects of ethanol and butanol as separate additives in biodiesel fuel on the spray and, combustion characteristics. The experimental results showed that ethanol and butanol blend can enhance spray and combustion characteristics of biodiesel. Wu et al. [10] examined the effect of butanol and ABE on spray behaviour under different temperatures and oxygen content in a CVV. The images of the experimental results showed that liquid penetration with n-butanol or ABE is much shorter than diesel under all tested conditions. Almost all the physical properties change with temperature: an increase in ambient temperature causes viscosity and surface tension to decrease and vapour pressure to increase; these changes significantly accelerate the atomisation and evaporation of the liquid spray.

A study by Chen et al. [11] investigated the spray and atomisation characteristics for commercial diesel fuel, biodiesel (FAME) derived from waste cooking oil (B100), and 20% biodiesel blended with diesel (B20). The experimental work was conducted at room temperature and pressure via a common-rail high-pressure fuel injection system with a single-hole nozzle for different injection pressures (300, 500, 800 and 1000 bar). The experimental results showed that biodiesel had different structures compared with conventional diesel fuel. Spray tip penetration was longer and droplet diameters were larger of pure biodiesel (B100).

Spray visualization of three fuel additives—butanol (B), BA and ABE has been investigated to determine the best

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type of alcohol blend to be used as an additive to conventional diesel.

2. Experimental apparatus

2.1 Fuel preparation and properties.

Analytical grade acetone (99.5% purity), normal butanol (99.5%) and ethanol (99.8%), supplied from Chem Supply Australia, were used. In this study, n-butanol (B) was the only butanol isomer used. In line with the intermediate products when producing B by fermentation, the volumetric ratio of acetone, butanol and ethanol was 3:6:1 in ABE and the volumetric ratio of butanol and acetone was 2.9:1 in BA. All alcohol blends were mixed together using splash blending at 4,000 rpm to simulate the composition of the above-mentioned ABE and BA fermentation products. Conventional diesel fuel supplied from a local petrol station in Toowoomba was used as the baseline fuel in this study. B, BA and ABE mixtures were blended with diesel by 10% volume and denoted 10B90D, 10BA90D and 10ABE90D, respectively. The miscibility and stability of B, BA and ABE-diesel blends were monitored over a three-month period before the tests were carried out on the engine. The samples were stored in glass bottles and visually observed every 30 days, with all blends maintaining a good homogeneous mixture. The density was measured for all fuel blends according to ASTM 1298. The dynamic viscosities of the test fuel were measured according to the ASTM 445-01 fuel standards by using a Brookfield DV-II+Viscometer, then the kinematic viscosity was calculated. The heating values of the blends were measured using a Digital Oxygen Bomb Calorimeter (XRY-1A) following ASTM D240. Each test was carried out in triplicate. The properties of diesel, acetone, butanol, ethanol and measured properties of fuel blends are listed in Table 1.

Table 1. *Measured properties of fuel blends.*

Blend	Density @ 20°C (g/L)	Viscosity @ 40°C (mm^2/s)	Heating value (MJ/kg)
Diesel	0.86	2.46	42.6
ABE	0.80	1	31.4
BA	0.79	1.03	32.2
10B90D	0.83	2.13	41.8
10ABE90D	0.83	2.21	41.4
10BA90D	0.82	2	41.3

2.2 Spray test setup

The experiment of spray test was conducted at atmospheric condition and consisted of: (1) A constant volume vessel (CVV), (2) a high pressure injection common rail system with Bosch electromagnetic (solenoid type injector was used due to this injector type widely used in diesel engines) and (3) visual data acquisition system. The spray images were captured using a Photron SA3 high speed camera. The CVV was illuminating using an LED light. Figure 1 shows experimental setup of spray system. The Injector specification, Camera specification and injection setup are listed in Figure 1. The Spray experiments followed three steps to ensure accurate results: (1) the fuel injection system (fuel tank, common rail and fuel line fittings) was emptied, cleaned and dried by an air compressor for each new blend test. (2) The fuel filter of each test was removed and replaced with a new one. After ensuring all the injection systems were cleaned and emptied, the spray testing started with a number of initial injections before the new images captured. (3) The spray test was repeated three times. The final spray characteristics were calculated by averaging the 6 plumes from the injector from all tests. Lights were installed on three of the windows and a high-speed camera on the fourth window for the purpose of spray visualisation. The inside of the vessel was painted black to ensure a good background for the images and to increase the images' contrast and enhance the visibility of the spray. The injector was mounted horizontally in the vessel so that all the spray axes are visualised through the front window. The definition of spray tip penetration is the distance between the nozzle tip and the maximum outer point of each spray.

The spray cone angle is the angle between two straight lines from the nozzle tip and the outer contour of the injected spray. The images were processed in three steps before quantifying the spray characteristics: (1) Images were read into MATLAB, then the recorded images were converted into binary images (2) An automatic threshold calculation algorithm was employed to determine the spray outline (edge) from the images. (3) Boundary pixels of each spray plume of each image were measured to quantify spray characteristics by measuring from spray contour. The flowchart of image processing is displayed in Figure 2

The fuel spray is assumed to occupy a cone with a hemisphere. The spray volume (V) was calculated as a function of spray penetration (S) and spray cone angle (θ) [12, 13]:

$$V = \left(\frac{\pi}{3}\right) S^3 \left[\tan^2(\theta)\right] \frac{1 + 2\tan\left(\frac{\theta}{2}\right)}{\left[1 + \tan\left(\frac{\theta}{2}\right)\right]^3} \quad (1)$$

Table 2. *Specifications of fuel injection system, camera specification and injection setup.*

Injector specification	
Injector type	Bosch electromagnetic common rail injector (solenoid type)
Number of injector holes	6
Hole diameter	0.18 mm
Injection quantity	12 mg
Injection enclosed angle	156°
Camera specification	
Camera resolution @ frame rate	1024×1024 pixels @ 2000 fps
Injection setup	
Injection pressure	300 and 500 bar
After start of injection time (ASOI)	0.5-1.5 ms

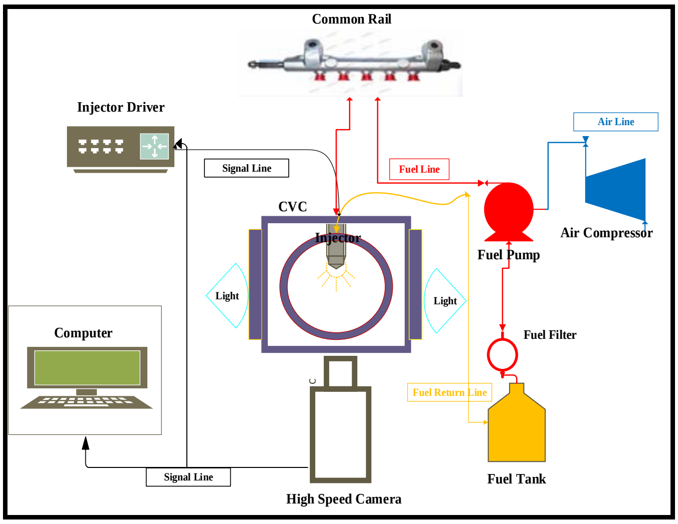

Figure 1. *Schematic of fuel injection system setup and visual data acquisition system.*

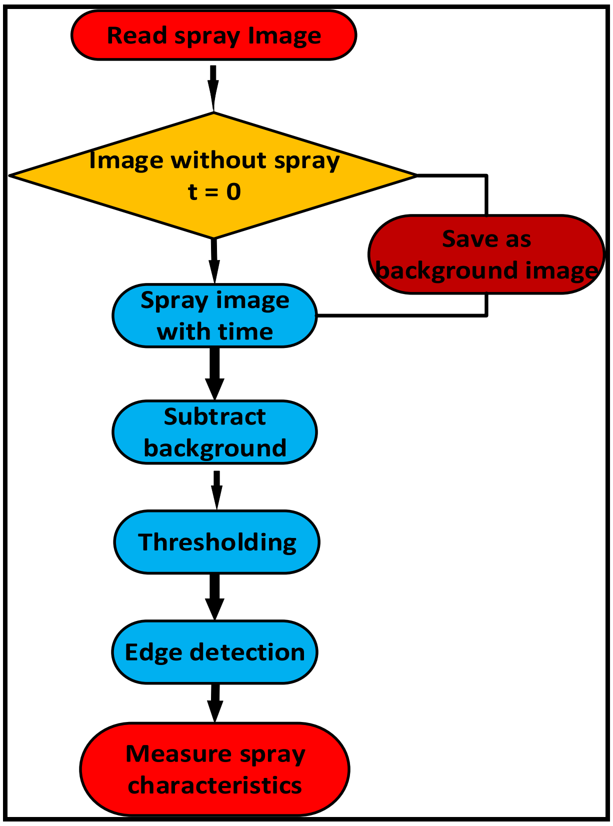

Figure 2. *Flowchart of image processing.*

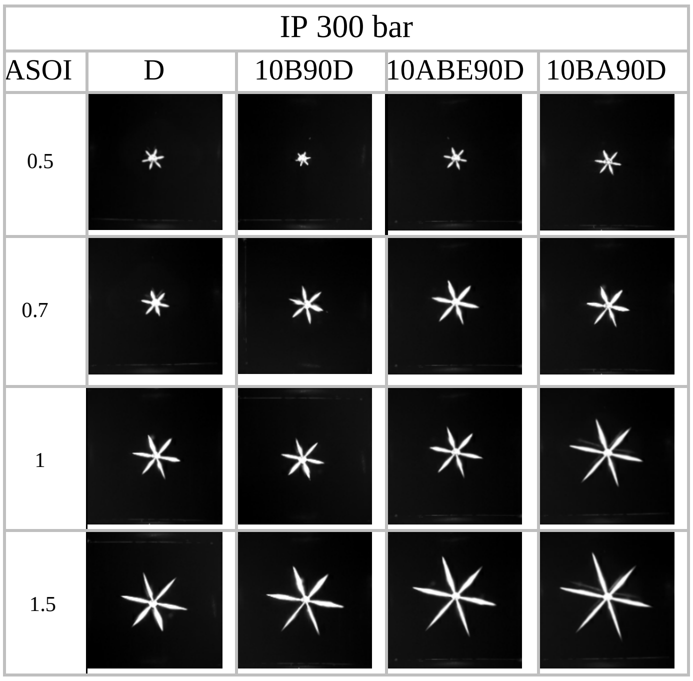

Figure 3. *Spray images of test fuels at injection pressures 300 bar.*

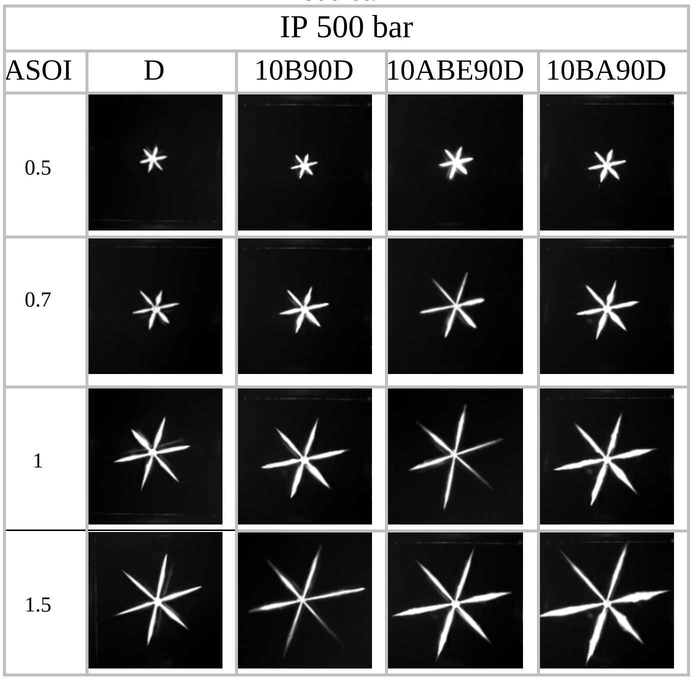

Figure 4. *Spray images of test fuels at injection pressures 500 bar.*

3. Results and discussion of spray test

3.1 Spray images

Spray images are derived from the triplicate tests. Rows from top to bottom show ASOI (Figure 3 and Figure 4). The scaling of spray images or spray pattern body became bigger as a result of increased ASOI and injection pressures (IP) values. Spray images of neat diesel fuel were used as a baseline. The spray characteristics were quantified from these images.

3.2 Spray tip penetration (S)

Figure 5 shows spray penetration of test blends. Alcohol-diesel blends showed increment in spray plumes area ranked from shortest to longest as: 100D, 10B, 10ABE and 10BA. Including acetone in ABE mixture and BA mixture improves the spray characteristics compared to pure butanol (B) due to its lower viscosity. A lower viscosity reduces the friction between fuel and the surface of injector nozzle hole, which causes a higher fluid velocity exiting from the injector nozzle. Fuels that have lower boiling points and higher heats of evaporation, such as alcohols (B, ABE and BA), can improve the evaporation rate. In an internal combustion engine, the process of atomization of the fuel spray is an important mechanism in which the fuel is mixed effectively within the gas combustion chamber. Therefore, atomization and combustion rate will be increased. The high spray area (longer spray tip penetration) can enhance air-fuel mixing rate and better combustion efficiency due to the increased surface area of contact between fuel and air.

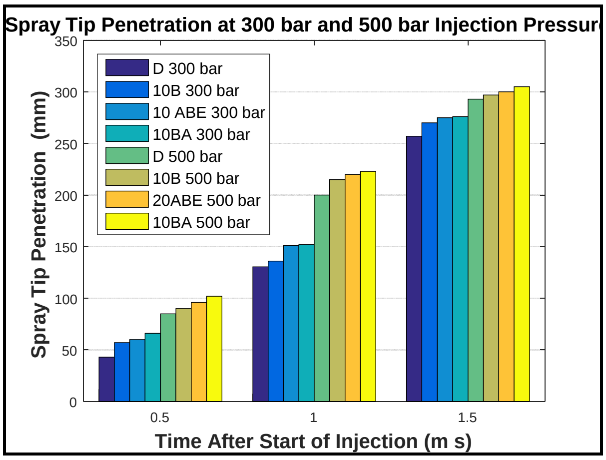

Figure 5. *Spray penetration of test fuels at injection pressures 300 bar and 500 bar.*

3.3 Spray cone angle (θ)

All alcohol blends showed slightly widened plumes (Figure 6). The increase in injection pressure leads to a slightly narrowed spray cone. When there is an insufficient radial momentum to overcome penetration resistance and the pressure difference across the sheet, then spray shoulders become strongly curved.

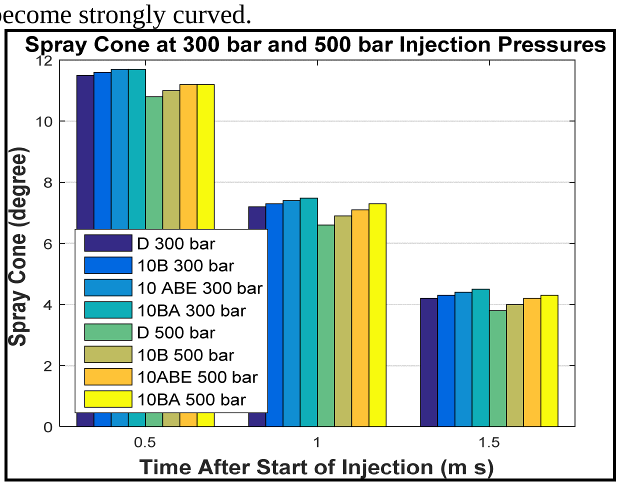

Figure 6. *Spray cone angle of test fuels at injection pressures 300 bar and 500 bar.*

3.4 Spray volume (V)

The spray volume of the test blends is presented for both injection pressures. The spray volume is calculated as a function of spray penetration (S) and spray cone angle (θ) under different injection conditions. The spray volume of the alcohol-diesel blends was higher than neat diesel due to their higher spray penetration length. Therefore, the contact surface area between the air and fuel would be increased, thereby resulting in increased mixing and reaction rates.

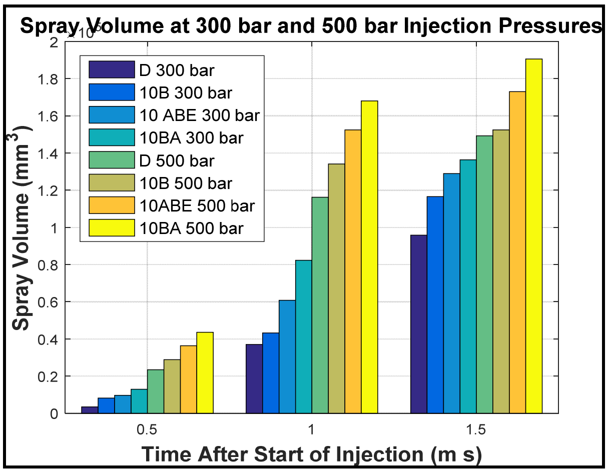

Figure 7. *Spray volume of test fuels at injection pressures 300 bar and 500 bar.*

4. Conclusions

High-alcohol chains of 10% B, BA and ABE and neat diesel were tested in a CVV to investigate the effect on spray characteristics. It was found that spray penetration was increased as a result of addition of any alcohol blends to diesel fuel as well as of increased injection pressure. Spray cone angle (θ) was slightly widened while it was slightly narrowed as a consequence of increased fuel injection. Spray penetration and spray volume of BA-diesel blend was higher compared to ABE-diesel and B-diesel blends. BA-diesel blends could be best blend for enhancing the spray characteristics of neat diesel, namely improved atomisation and evaporation rate compared to pure butanol (B) and ABE-diesel blends. Then, combustion behavior and engine performance of BA-diesel blend could be enhanced as a result of improved spray characteristics compared to other blend.

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