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Impact of butanol-acetone mixture as a fuel additive on diesel engine performance and emissions

Sattar Jabbar Murad Algayyim[a,d,*], Andrew P. Wandel[a,b], Talal Yusaf[a], Saddam Al-Lwayzy[c], Ihsan Hamawand[c]

[a] School of Mechanical and Electrical Engineering, University of Southern Queensland, Toowoomba, QLD 4350, Australia
[b] Computational Engineering and Science Research Centre, University of Southern Queensland, Toowoomba, QLD 4350, Australia
[c] National Centre for Engineering in Agriculture (NCEA), University of Southern Queensland, Toowoomba, QLD 4350, Australia
[d] Department of Mechanical, College of Engineering, University of Al-Qadisiyah, Al-Diwaniyah, Iraq

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ABSTRACT

Butanol-acetone (BA) mixture is considered a green energy resource because it releases fewer emissions than other fuels. BA can produce via fermentation from biomass (agricultural waste and residues) that is non-edible. The benefits of butanol have been supported by many studies as additive fuel for conventional diesel due to its exceptional fuel properties such as high burning velocity and heating value. However, the cost of butanol production is the main issue of using it as a fuel because of high recovery and production costs. It is cheaper to produce BA than butanol because it is not necessary to separate the butanol from other chemicals in the biofuel. Many researchers have investigated the fermentation process to produce a fuel mixture of acetone-butanol-ethanol (ABE) with a 3:6:1 ratio. However, a number of studies demonstrate the drawbacks of using ethanol as an additive for diesel engines because of unsuitable properties for diesel engine such as lower heating value, cetane number and corrosion behaviour so BA with no ethanol is a better additive for diesel than ABE.

This paper investigates the effect of using a butanol/acetone (BA)-diesel blend on exhaust gas emissions and engine performance. The test was performed for different blend ratios of BA to diesel (10BA90D, 20BA80D and 30BA70D) at engine speeds of 1400, 2000 2600 RPM in a single-cylinder diesel engine. This study has shown that brake power (BP) is maximum at 10% BA at all engine speed, approximately 5% higher than D100. The brake thermal efficiency (BTE) of 10% BA was comparable with D100 at all engine speeds, but was slightly increased by 6% and 8% at all engine speeds when the BA ratio was 20% and 30% respectively. CO emission levels have a significant decrease for all BA blend with a maximum 64% reduction than D100; CO_2 emission was correlated with BP; NO_x decreased at all BA blend with a maximum 10% reduction than D100; and the exhaust gas temperature decreased for all BA blend by 15.6% compared to D100. BA is shown to be a good renewable fuel additive to diesel because it can improve energy efficiency and reduce pollutant emissions.

1. Introduction

Due to population growth together with environmental concerns, there is significant demand for carbon-neutral fuels in addition to more stringent legislation governing engine pollutant emissions. This has been attracting new interest in renewable, sustainable and environmentally - friendly energy resources [1,2]. Many techniques have been applied to reduce emissions levels and improve fuel efficiency. The use of additives such as ethanol and butanol in fossil fuels has been investigated extensively and is commercially available [3]. The experimental results of these additives revealed significant reductions in Particulate Matter (PM), hydrocarbon (HC) and carbon monoxide (CO) concentrations [4,5]. Another advantage of using alcohol additives is that they can be derived from renewable biomass resources such as residual agricultural biomass and wastes [6]. These biomass sources are widely available, but it is currently a challenging process to convert them into alcohol biofuels. Among various alcohols, ethanol is the earliest one to be put into the market [7], however some safety and technical concerns remain unresolved [8].

ABE is a combination of acetone, butanol and ethanol, which is

Abbreviations: ABE, acetone:butanol:ethanol; IBE, isopropanol:butanol:ethanol; BA, butanol:acetone; BP, brake power; BTE, brake thermal efficiency; BSFC, Brake specific fuel consumption; CA, crank angle; CO_2, carbon dioxide; CO, carbon monoxide; C_v, specific heat for constant volume; C_p, specific heat for constant pressure; EGT, exhaust gas temperature; NO_x, nitrogen oxides; PM, particular matter; TDC, top deep centre; UHC, unburnt hydrocarbon; θ, crank angle; γ, ratio of specific heats

* Corresponding author at: School of Mechanical and Electrical Engineering, University of Southern Queensland, Toowoomba, QLD 4350, Australia.
E-mail address: Sattarjabbarmurad.algayyim@usq.edu.au (S.J.M. Algayyim).

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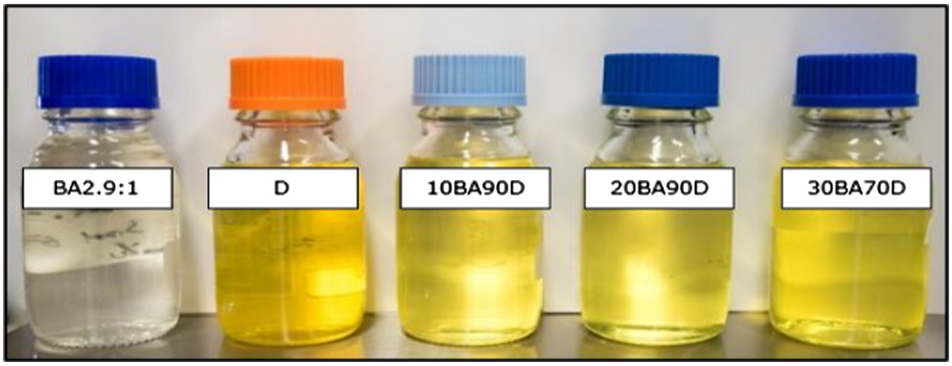

Fig. 1. Blend mixture over a period of 4 months storing.

another suitable fuel additive that can be produced from biomass via fermentation. This fuel has attracted researchers' attention due to its better performance as a blend when compared to ethanol. ABE is typically produced in a volumetric ratio of 3:6:1 from the fermentation process [9–19]. The ABE mixture can be further purified to obtain pure acetone and/or butanol. However, the purification processes significantly increase the production cost. It is preferable to use ABE as a mixture because butanol is the most abundant component in the ABE mixture. Butanol provides a higher energy content compared to ethanol and has physical properties more similar to commercial transportation fuels. Some researchers have tested the ABE mixture experimentally in CI engines. Van et al. [20] showed that ABE's laminar flame speed is higher than acetone and lower than ethanol and butanol. Other researchers [21–32] have studied the impact of ABE on various formulations of ABE (A:B:E 6:3:1, 3:6:1 and B) and ABE-diesel blends (D100, ABE20D80, ABE50D50 and ABE80D20) on spray and combustion behaviour in a constant-volume chamber. The results indicated that: ABE decreases the ignition delay and combustion temperature; soot and NO_x were remarkably reduced. The heat release rate curve of ABE20 (6:3:1) was very similar to that of D100 in terms of the ignition delay and initial premixed combustion, while the heat release rate curve of ABE20 (3:6:1) was closer to that of butanol.

Lin et al. [27] have experimentally investigated the effect of ABE-diesel blends on common-rail diesel engine performance. The results showed that addition of ABE to diesel increased the thermal efficiency and significantly reduced NO_x and soot emissions with up to 20% vol. of ABE addition to the blend. Zhao et al. [28] studied experimentally and numerically the soot mechanism of ABE with various oxygen concentrations. A multi-step ABE phenomenological soot model was proposed and implemented in the KIVA-3V Release 2 code. The results indicated reduction of soot particles under highly-diluted oxygen conditions.

Ma et al. [29] performed a droplet evaporation test of an ABE and diesel mixture in a non-combusting droplet chamber at high ambient temperatures. It was observed that the addition of the ABE mixture enhanced the evaporation speed of the droplet and thus reduced the lifespan of the droplet. Li et al. [30] studied also isopropanol-n-butanol-ethanol (IBE) as additive for gasoline with different blends ratio. It was found that IBE30 reduced CO and NO_x by (4%) and (3.3–18.6%) respectively, compared to gasoline. A number of studies [33,34] demonstrated some drawbacks when using ethanol as an additive for diesel engines because of the lower heating value and cetane number, and its corrosive behaviour. As ethanol is one of the components in ABE, another alcohol mixture, butanol-acetone (BA), has emerged. BA has a higher fraction of butanol (75%) than ABE and it does not contain ethanol. In a study by Li et al. [35], BA was produced via fermentation of cassava substrate with a ratio of 2.9:1 BA.

To our knowledge, BA as an additive to diesel fuel has not yet been investigated. In this article, a BA-diesel fuel blend was investigated in a single-cylinder diesel engine. Both the performance of the engine and exhaust emissions were tested evaluated and compared with diesel fuel.

2. Methodology

2.1. Fuel preparation and properties

Butanol-acetone was prepared with a ratio 2.9:1 using 99.8% analytical grade chemicals. The butanol used was *n*-butanol and diesel from a local petrol station. The BA (290 ml of butanol + 100 ml of acetone mixed together) which was used to simulate the intermediate product of the BA fermentation was mixed using splash blending and was blended at 4000 rpm to emulate the composition of the above-mentioned BA fermentation product.

The BA blend was blended with diesel in three ratios 10%, 20% and 30% by volume: 10BA90D, 20BA80D, and 30BA70D. Miscibility and stability of BA-diesel blends was monitored before the tests run on the engine. The visualization result of blend stability observed that there was no separation in the BA-diesel blends. Moreover, the stability of blends for phase separation was observed over a period of 4 months by storing the blends in a glass bottle (Fig. 1) the samples were visually observed every 30 days. It was observed that 10, 20 and 30% of BA blends maintained a good homogeneous mixture over a 4-month timeframe.

The density was measured for all fuel blends at 20 °C room temperature. The viscosity (kinematic viscosity at 40 °C) of the blend was measured using a Brookfield Viscometer DV-II + Pro Extra. The heating values of the blends were measured using a Digital Oxygen Bomb Calorimeter (XRY-1A). Each test was carried out in triplicate. Tables 1 and 2 illustrate the blend properties of all samples.

2.2. Engine test setup

The experiment was conducted using a G.U.N.T Hamburg single-cylinder direct injection (DI) diesel engine, designed for experimental

Table 1
Diesel fuel, *n*-butanol and acetone specifications [27,30,36].

Fuel properties	Diesel[a] fuel (C4-C12)	*n*-butanol[b] ($C_4H_{10}OH$)	Acetone[b] (C_3H_5OH)
Density @ (20 °C) (g/mL)	0.82–0.86	0.813	0.791
Viscosity@(40 °C) (mm^2/s)	1.3–2.4	2.63	0.35
Lower heating value (MJ/kg)	42.7	33.1	29.6
Auto ignition temp (°C)	230	343	465
Boiling point (°C)	180–360	118	56
Cetane number	50	≅25	

Notes:
[a] Properties of diesel are from [22].
[b] Properties of butanol and acetone are from [25,29].