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Effect of *n*-butanol and diethyl ether as oxygenated additives on combustion–emission-performance characteristics of a multiple cylinder diesel engine fuelled with diesel–jatropha biodiesel blend

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ABSTRACT

Jatropha biodiesel is considered as one of the most prospective renewable energy sources of Malaysia in recent years. Hence, an investigation was conducted for the improvement of jatropha biodiesel–diesel blend with the addition of 5–10% *n*-butanol and diethyl ether by vol. which are commonly known as oxygenated cold starting additive. Engine tests were conducted at variable speed, ranging from 1000 rpm to 3000 rpm at constant 80 N m torque on a 4-cylinder turbocharged indirect injection diesel engine. Engine performance parameters like brake specific fuel consumption, brake specific energy consumption, brake thermal efficiency and engine emissions like carbon monoxide, unburned hydrocarbons, nitrogen oxide and smoke opacity were measured. Performance and exhaust emissions variation of the modified blends from the baseline fuel (jatropha biodiesel–diesel blend) were compared for the assessment of the improvement quantitatively. In-cylinder pressure diagram of all the test fuels were acquired and the heat release rate analysis was conducted at different operating conditions to explore the features of combustion mechanism and correlate them with the performance and emission characteristics to acquire better understanding of the scenario. However, in a nut-shell, the investigation reveals the potential of *n*-butanol and diethyl ether to be used as the additive of jatropha biodiesel–diesel blend in the context of combustion, performance and emission characteristics.

1. Introduction

Biodiesel refers to the fatty acid methyl esters which are derived from lipid substances from oils, fats, waste greases, recycled oils, etc. To produce biodiesel, vegetable oils of edible origin were treated as one of the potential feedstocks once. Due to food vs. fuel controversy of usage of edible oil for fuel production, other sources e.g. non-edible oils of plant origin with high free fatty acid (FFA) content, etc. are now being used for biodiesel production. Malaysia is one of the leading palm oil producers in the world [1]. In addition, it also facilitates the use of palm oil as fossil diesel replacement. The government of Malaysia has recently mandated the use of 5% palm biodiesel with diesel nationwide for all diesel vehicle [2]. However, because of the edible nature of the palm oil, recently jatropha has drawn immense attention of both private and government sectors in Malaysia. *Jatropha curcas* is non-edible in nature, physicochemical properties of its biodiesel are quite similar to the palm biodiesel and most interestingly, it has been reported as one of the best contestants of cheap biodiesel source in future [3]. Hence, Malaysian government started a project concerning jatropha cultivation and economic viability study of jatropha biodiesel production [4]. It has been reported that, Forest Research Institute of Malaysia (FRIM) has completed a 6000 *J. curcas* tree plantation project and the agency has confirmed that it is ready to proceed to commercial scale [5]. Therefore, being a prospective non-edible renewable energy source with satisfactory physicochemical properties, jatropha biodiesel deserves profound investigation regarding its viability in the diesel engines.

Many experiments were done with neat jatropha biodiesel or its blends with diesel to study their effects on engine performance and emission characteristics. Huang et al. [6] studied with jatropha biodiesel and reported 3.6% higher brake thermal efficiency (BTE) compared to diesel at higher loads in expense of higher brake specific fuel consumption (BSFC). Sundaresan et al. [7] also found from their study that the engine efficiency and BSFC for jatropha were inferior to that of diesel fuel. However, pre-heating and blending

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with diesel have been reported conducive for engine performance characteristics [8]. Manieniyan and Sivaprakasam [9] reported significant improvement of performance while they tried 20% blend of jatropha biodiesel which was also supported by the work of Sahoo et al. [10]. Therefore, blending with petroleum diesel as a single biodiesel [11] or as an optimized multiple biodiesel blend [12] have already been studied by several researchers.

The problems associated to biodiesel is its high viscosity and auto ignition temperature (AIT) compared to that of diesel. To minimize these drawbacks as well as to increase the fuel bound oxygen (to facilitate combustion) and to keep lubricity at reasonable levels, oxygenated additives such as *n*-butanol and diethyl ether (DEE) are usually added in a small portion [13]. *n*-butanol has emerged as a potential oxygenated additive to improve the fuel properties of both diesel and biodiesels recently. *n*-butanol, also better known as 1-butanol, is produced from alcoholic fermentation of biomass feedstocks [14]. Hence, it is a renewable additive with a straight-chain structure with the OH group at the terminal carbon. *n*-butanol is a strong competitor of ethanol and has less hydrophilic tendency, higher cetane number, higher miscibility with diesel and biodiesels and higher calorific value [15]. Yao et al. [16] investigated the influence of *n*-butanol-diesel blend on the performance and emissions of a heavy-duty diesel engine with multi-injection and various EGR (exhaust gas recirculation) ratios. They reported that, the soot and CO emissions can be improved by the addition of *n*-butanol without a severe impact on the BSFC. Altun et al. [17] studied the effect of *n*-butanol on cottonseed biodiesel–diesel blend and reported that, emissions of NO_x, HC and CO reduced in expense of higher BSFC. Lebedevas et al. [18] experimented with butyl esters of rapeseed oil-diesel blend with the addition of 15–25% *n*-butanol and reported improvement on emission characteristics and overall efficiency factor. In their study, Mehta et al. [19] studied the effect of varying percentage of *n*-butanol with jatropha biodiesel–diesel blend and reported significant reduction in CO and NO emission in expense of lower engine performance. However, they did not analyse their data with sufficient insight on combustion phenomena at each condition. Thus, the disadvantage of higher viscosity of biodiesel and the lower cetane number of *n*-butanol than biodiesel can be offsetted with the addition of *n*-butanol as additive.

Diethyl ether is another biomass based oxygenated additive produced from ethanol, which is produced itself from biomass [20]. It is a colorless liquid with high volatility and flammability. It has got very high cetane number, reasonable energy density and low AIT with high oxygen content. It has high miscibility with both diesel and biodiesel. Consequently, it is very much suitable to be used in diesel engine either with diesel or biodiesels [21]. Many researchers have studied diesel-DEE blend to improve the performance and emission characteristics. Blending with neat biodiesel or biodiesel–diesel blend has also been tried by the researchers. Babu et al. [22] evaluated the effect of DEE on mahuva methyl ester and reported that, CO and smoke emission decreased more than 50% after addition of DEE. Sivalaksmi and Balusamy [23] added 5–15% DEE on neat neem biodiesel and reported improvement of BSFC and BTE. Qi et al. [24] studied effect of 5% DEE addition with soybean biodiesel–diesel blend. They observed significantly lower CO emission with better BSFC with the addition of DEE into the diesel–biodiesel blend. Thus, it can be concluded that, addition of DEE results in improved performance and emission characteristics of diesel engines.

Jatropha biodiesel has the potential to be used as partial replacement of diesel in Malaysia after palm oil. Therefore, an attempt was taken previously by the authors for the improvement with the addition of *n*-butanol and DEE [4]. On that investigation it was observed that addition of 5% *n*-butanol and DEE improved the brake power (3.5%), brake thermal efficiency (3.4%) and also reduced the emissions of NO_x (9%), CO (20%) and smoke opacity (22%) of the modified blends than J20 blend on average with an unmodified single cylinder diesel engine. Apart from that, there is an absence of comparative study in the literature on the effects of higher percentages of *n*-butanol and DEE as additives on jatropha biodiesel–diesel blends on multiple cylinder engines. Therefore, in the present investigation the authors have attempted to increase the percentage of *n*-butanol and DEE in the quest of studying the effects in a four cylinder, water cooled turbocharged diesel engine. In addition, combustion analysis has been incorporated at different operating conditions to get in-depth understanding of the combustion mechanisms and their correlation with the performance and emission characteristics. Cost analysis of all the modified blends have also been incorporated into this study to provide an economic comparison of different tested fuels.

2. Materials and method

2.1. Feedstock and additive

FRIM (Forest Research Institute Malaysia) supplied the jatropha biodiesel. *n*-butanol and DEE were purchased from Nacalai Tesque, Inc., Kyoto, Japan; certified as 99.5% pure. Petroleum diesel was supplied from the local market supplier.

2.2. Fatty acid composition (FAC)

In this investigation Shidmadzu, GC-2010A series gas chromatograph was used to explore the FAC of jatropha biodiesel. Tables 1 and 2 show the GC operating conditions and the FAC results of the biodiesel. Jatropha biodiesel contains 24.3% saturated, 42.6% mono-unsaturated and 33.1% poly-unsaturated methyl esters. Higher portion of saturation indicates higher oxidation stability and CN (cetane number). On the contrary it also indicates lower iodine value and CFPP according to the literature review [25].

2.3. Test fuels

The preparation of the test fuels and characterization of the properties were carried out at the Engine Tribology Laboratory, Department of Mechanical Engineering, University of Malaya. A total of six test fuels were selected for this investigation. The test fuels were (a) 100% petroleum diesel, (b) 20% Jatropha biodiesel + 80% diesel (J20), (c) 15% Jatropha biodiesel + 5% *n*-butanol + 80% diesel (J15B5), (d) 10% Jatropha biodiesel + 10% *n*-butanol + 80% diesel (J10B10), (e) 15% Jatropha biodiesel + 5% DEE + 80% diesel (J15D5), (f) 10% Jatropha biodiesel + 10% DEE + 80% diesel (J10D10). The proportions mentioned here were all volume based. Diesel and biodiesel blending was completed

Table 1
GC operating condition for determination of fatty acid composition.

Item	Specification
Column	0.32 mm * 30 m, 0.25 μm
Injection volume	1 μm
Carrier gas	Helium, 83 kPa
Injector	Split/splitless 1177, full EFC control
Temperature	250 °C
Split flow	100 mL/min
Column 2 flow	Helium at 1 ml/min constant flow
Oven	210 °C isothermal
Column temperature	60 °C for 2 min
	10 °C/min to 200 °C
	5 °C/min to 240 °C
	Hold 240 °C for 7 min
Detector	250 °C, FID, full EFC control